Systems Engineering Paper

Lunar Regolith Excavator

Team Golden Eagles

Billy Strnad
Susanna Whittaker
Marshall Nicholson
Michael Anthes
David Penner

National Aeronautics and Space Administration (NASA)

Washington, D.C.

University Advisor
Dr. Will Holmes

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JOHN BROWN UNIVERSITY

Table of Contents

Introduction....1
Systems Engineering....1
Missions Objective....2
System Requirements....2
Concept of Operations....3
Major Reviews....3
Interfaces....3
Frame Subsystem....4
Mobility Subsystem....5
Excavation Subsystem....7
Storage/Ejection Subsystem....8
Power....9
Control Subsystem....11
Communications....13
Requirement Flow-Down to Validation Check Out....14
System Integration....15
Use of Systems Life Cycle....15
Configuration Management....15
Project Management....15
Conclusion....15
Appendix A: Lunabotics Mining Competition Rules....18
Appendix B: System Requirements Review....32
Appendix C: Mass Budget....36
Appendix D: Power Budget....37
Appendix E: Preliminary Design Review....38
Appendix F: Critical Design Review....47
Appendix G: Interfaces....54
Appendix H: Mobility Trade-Off Assessment....55
Appendix I: Complete Risk Analysis....56
Appendix J: Excavation Trade-Off Assessment....66
Appendix K: Storage/Ejection Trade-Off Assessment....67
Appendix L: Power Testing....68

Appendix M: Power Trade-Off Assessment 75
Appendix N: Control System Details 76
Appendix O: Control System Trade-Off Assessment 77
Appendix P: Communication System Details 78
Appendix Q: Communication Trade-Off Assessment 80
Appendix R: Schedule 81
Appendix S: Budget 83

Introduction

The National Aeronautics and Space Administration (NASA) is hosting the second annual Lunabotics Mining Competition (LMC) May 23-28, 2011[1-3]. NASA designed the competition to "engage and retain students in science, technology, engineering and mathematics"[1]. The main competition objective is for university teams to design, build and test a robot to demonstrate lunar excavation concepts. The robot must be operated remotely or autonomously to excavate and deposit a minimum of 10 kg of lunar simulant within 15 minutes.

To achieve this goal, the John Brown University (JBU) team followed a systems engineering approach. The team derived requirements for their design from the LMC rules[2] as well as testing the 2010 JBU Lunabot[4]. The team found that the 2010 JBU Lunabot needed major improvements in the power the batteries provided to the mobility system, the maneuverability of the mobility system, and the method of excavation.

The team divided the Lunabot design problem into subsystems and defined subsystem level requirements as well as interfaces between subsystems. Once the team designed each subsystem to meet the derived requirements, the team performed component level testing and subsystem level testing before integrating subsystems and performing system level testing. As of the writing of this paper, the team has created a working prototype which has undergone ten hours of competition style system testing. Through this testing, the Golden Eagles Lunabot demonstrated its ability to successfully complete mission requirements. Also, integration was very smooth as there was only one unanticipated issue which arose during system integration. The team contributes the ease of integration of the subsystems to the systems engineering approach as well as comprehensive testing at all levels of the system.

Figure 1: Lunabot Prototype

The team consisted of five senior level engineering students. Four of the five team members took on the role of subsystem leads, the fifth member took on the role of chief systems engineer. The team met weekly with their faculty advisor for suggestions and input on the project. The team also held a weekly dinner to bond as a team outside of the project. The team cooperation and interaction was another key aspect of successfully creating a robot which has demonstrated its ability to meet requirements.

This paper demonstrates how the team applied systems engineering to the NASA LMC. The team defined the mission objective and system level requirements, created a concept of operations, held major reviews, and defined interfaces. From these the team designed subsystems. Each subsystem underwent the same process as the system as a whole and were presented during major reviews. The balance of this paper describes this process. We first describe this process for the entire robot and then for each subsystem.

Systems Engineering

The systems engineering approach is crucial in designing a complex system. The JBU team followed the systems engineering phases created by Dr. David Beale shown in Figure 2[5] and applied the 11 systems engineering functions shown in Figure 3[5].

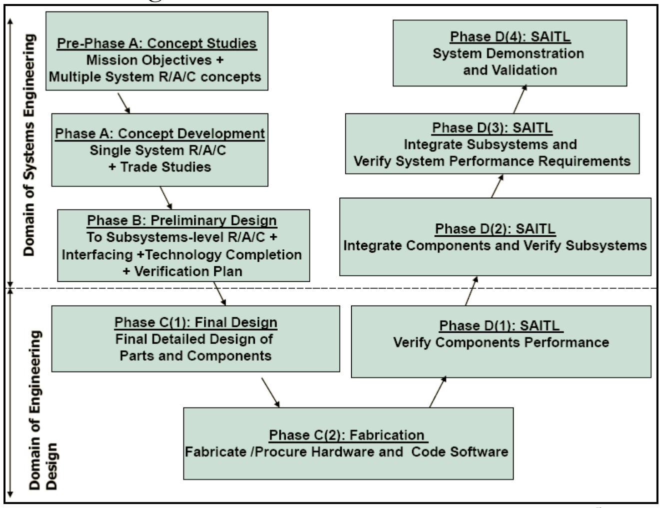

Figure 2: Systems Engineering Vee Chart from Beale[5]

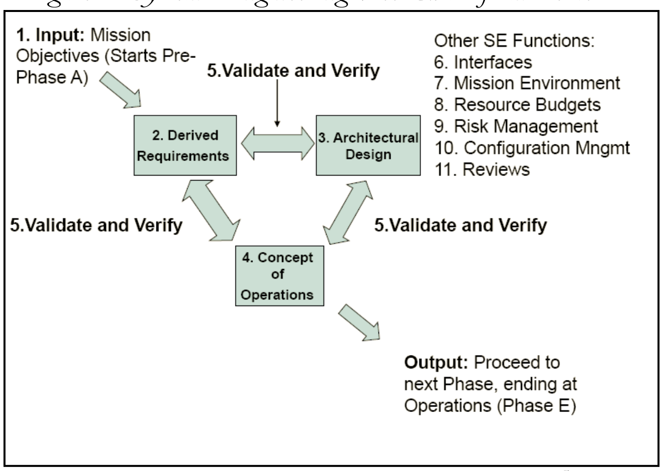

Figure 3: 11 Functions Engineering from Beale[5]

Design of the robot served as partial fulfillment of requirements for senior design at JBU which is a two semester sequence. The team spent the first semester of their senior design class performing phases A through B. The second semester the team completed Phase C through Phase D.

JBU was involved in the NASA LMC in 2010, the first year the competition was held. The current team analyzed the previous year's design and created a new design based on the performance of the previous prototype.

At this time, the team has created a prototype and performed testing on all subsystems and the integrated system as a whole.

Missions Objective

The mission of the Golden Eagles is design a robot for competition in the 2011 NASA Lunabotics Mining Competition.

System Requirements

The main goal of the system is to compete in the NASA LMC, therefore the system requirements are derived mainly from the competition rules found in Appendix A. The team wishes to go above and beyond the competition requirement of collecting 10 kg of simulant, and collect enough regolith to obtain first place. This goal changed our system requirement of collecting 10 kg to 100 kg of simulant, 10 times the required amount. The system requirements were divided into the following categories: functional, performance, interface, verification and other. These system requirements drive all of the subsystem requirements and can be found in Table 1 along with reference numbers for each requirement.

Table 1: Table of System Requirements

System Requirements:	
Functional	Excavate, carry and eject 100 kg of simulant (F.1)
	Eject simulant into hopper 1 m above surface (F.2)
	Fit within 1.5 m x .75 m x 2 m (F.3)
	Weigh less than 80 kg (F.4)
	Average use of less than 5MbBW (F.5)
	Operable from alternate location (F.6)
	Maneuverable across Lunarena of simulant with obstacles and craters (F.7)
Performance	Excavate 100 kg simulant in 15 minutes (P.1)
Interface	Operable within NASA's network (I.1)
	Not interfere with other team's performance (I.2)

(Table Continued on next page)

Table 1: Table of System Requirements (Continued)

Verification	Functional within test Lunarena (V.1)
	Functional within test network (V.2)
	Functional for half hour with all systems continual operation (V.3)
Other	Monitor battery health, all current usage, regolith excavation and storage, position, and bandwidth measurement (O.1)

Concept of Operations

From the system requirements, we created a Concept of Operations. Table 2 shows a breakdown of the competition time.

Table 2: Concept of Operations

Competition Time Budget		
Time (Minutes)	% of Total Time	Description
1	6.67	Establish communications and initialize systems
2	13.33	Move into position and cross obstacle zone
1	6.67	Move into position and prepare for mining
6	40	Mining
2	13.33	Retract excavation system and cross obstacle course
2	13.33	Position Lunabot at the hopper
1	6.67	Deposit regolith
15	100	Total

The Concept of Operations was derived from the functional systems requirements. The team designed the system to operate with only one cycle; this was to reduce the risk while traversing the obstacle zone and while ejecting the regolith.

Major Reviews

During the fall semester of 2010, the team presented their system requirements to their faculty advisor as their Systems Requirement Review (SRR). Appendix B shows the system requirements along with the subsystems requirements the team presented during the SRR. A major outcome of this review was confirmation of the concept of operations shown in Table 2 as well as the mass and power budgets shown in Appendix C and D, respectively.

The Golden Eagles held their Preliminary Design Review (PDR) on November 11 2010. During the PDR, the team presented how they divided the overall system into the subsystems. The PDR required the team to solidify their design by presenting their concept of operations and initial design options shown in Appendix E. One of the major outcomes of the PDR was the team's decision that the control subsystem would use an Arduino microcontroller as opposed to a Gumstix microcontroller using Space Plug-and-Play Avionics (SPA)[6-8] protocol. This was to reduce complexity and risk of this critical system.

The team's Critical Design Review (CDR) was the week of February 15th, 2011. The reviewers consisted of nine different individuals including JBU engineering faculty and staff and machinists from a local machine shop. The team split the CDR into two reviews, one for the electrical subsystems and one for the mechanical subsystems. Appendix F shows the slides for this design review. All team members were present for each CDR.

One critical decision made in the electrical CDR was to use only one instead of two Arduino boards for the Control Subsystem. This reduced the complexity of the design as well as the mass of the Lunabot. The mechanical CDR confirmed the design decisions and no major changes were made.

Interfaces

As the team created the concept of operations, the team divided the system into two subsystems - mechanical and electrical. Figure 4 shows the product hierarchy of the electrical and mechanical subsystems.

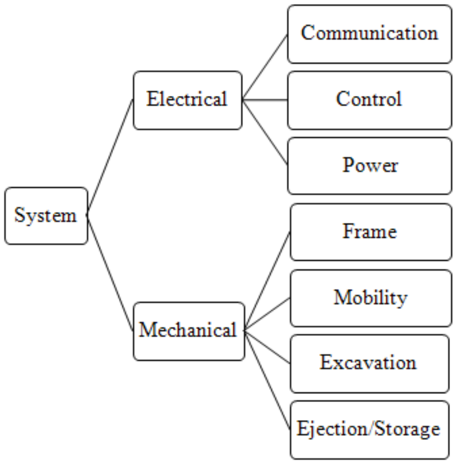

Figure 4: System Hierarchy

During the brainstorming process, the team defined all interfaces as shown in Appendix G. Each subsystem was assigned to a team member. The communication, control and power subsystems were assigned to team members as their sole subsystem responsibility. The four mechanical subsystems, frame, mobility, excavation and ejection/storage subsystems were assigned to one team member. In the following sections the design process for each of the subsystems is described in detail.

Frame Subsystem

Concept of Operations/ Interfaces

All of the on-board electrical subsystems and components as well as the mechanical subsystems and components must be mounted on the frame during the competition. The frame will need to withstand any stresses from the movement of the Lunabot, the excavation process, the load being carried and the load being ejected. The frame subsystem was created to hold all the mechanical subsystems and components as well as all on-board electrical subsystems and components.

Requirements

Table 3 shows the main requirements for the frame subsystem.

Table 3: Frame Subsystem Requirements

Requirement	Basis
Carry a load of 180 kg while maneuvering through the Lunarena without significant deformation	System requirement F.1, F.4, V.1
Support and contain all subsystems within the envelope of 1.5m by 75m by 2m	System requirement F.3
Weigh less than 10.5kg	Mass budget

Trade-off Assessment

The 2009-2010 JBU team created their Lunabot with an 80/20[a] modularized aluminum frame. The current team chose to find a material that was lighter, just as strong but less expensive. While using 80/20 aluminum for the frame allowed for easy assembly, it is expensive and is more difficult to customize.

The team performed a trade study on the frame subsystem materials and decided to use 4130 Chrome-moly tubing. Figure 5 shows the frame subsystem 3D model.

Figure 5: 3D Model Frame Subsystem

[a] 80/20 is a modular framing system extruded from 6105-T5 aluminum alloy. http://www.8020.net/

Basis of Design

The system requirements dictate that the Lunabot fit within a 1.5 m x .75 m x 2 m envelope and weigh less 10.5 kg. Therefore, the team organized this function as a frame system under the mechanical subsystem. The team based the design on the ease of manufacturing, the strength of the material, and the mass of the material. The team designed the frame to hold the mechanical subsystem components and the electrical on-board subsystem components.

Subsystem Hierarchy

Figure 6 shows the system hierarchy for the frame subsystem.

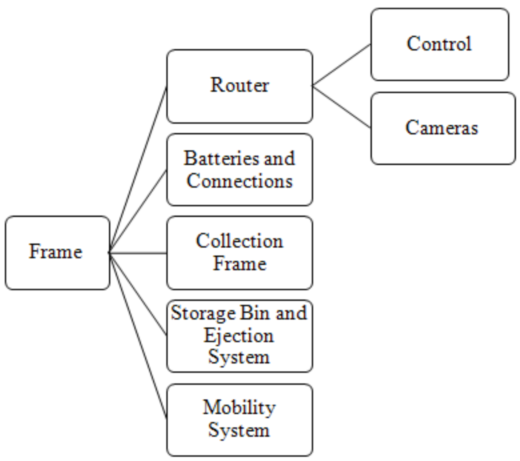

Figure 6: Frame Subsystem Hierarchy

Design Margins

The team designed the robot to operate under a loading of 100 kg of simulant. Therefore, the frame will be operating under a load of almost 180 kg. For the frame subsystem, the team designed a safety factor into all members of the frame; the minimum factor of safety in any member was 1.3 for 100 kg of regolith collected.

Risk Assessment

Table 4: Frame Subsystem Risks

Risk	Mitigation Strategy
Frame fails due to bending	A factor of safety was built into the design.

Verification

The frame system was tested initially with 100 kg of loading after being integrated with the mobility system. The team found that no significant deformations took place. The frame was also tested with 100 kg of loading after being integrated with the excavation/storage subsystems, finding the same results as initial testing. To meet system requirement F.3, once integration of all subsystems occurred, the dimensions were measured and found to be under the required envelope.

Reliability

During the verification process it was found that the frame was 100% reliable for the system requirements.

Mobility Subsystem

The system requirements dictate a mobile robot. Therefore, the team organized this function as a mobility subsystem under the mechanical system. The main requirement for this subsystem is that the Lunabot be easily maneuvered in the regolith simulant while carrying a load of 180kg.

Concept of Operations

Once the competition has begun, the Lunabot will initially be placed at a random orientation. It will then:

- Position to traverse obstacle zone
- Move across obstacle zone, avoiding rocks and straddling craters
- Stop in excavation zone and begin excavation, must be able to creep while excavation system operates
- Position to traverse back across obstacle zone
- Move across obstacle zone while carrying load of 180 kg avoiding rocks and straddling craters
- Position for ejecting regolith
- Stop while ejecting

Interfaces

The mobility system attaches to the frame at specific locations on the frame's lower tubing. It receives control signals from the control subsystem in the form of serial data signal to the speed controller and pulse width modulation to the motors. Each motor receives power from the power subsystem with 24 Volt draws between 8 and 12 Amps.

Requirements

Table 5 shows the driving requirements for the mobility subsystem.

Table 5: Mobility Subsystem Requirements

Requirement	Basis
Distance between ground contact greater than 30 cm	System requirement F.7
Enough power to carry 180kg	System requirement: F.1, F.4
Must be capable of varying speeds	System requirement F.7
Must weigh less than 24kg	Mass budget

Basis of Design

Based on these requirements and knowledge of lunar simulant[12], the team chose a four wheel skid-steer design. To power the mobility subsystem, we chose two wheelchair motors. The power and gearing were driven by the self-imposed requirement that the robot be able to execute a near zero radius turn in the lunar simulant. Figure 7 shows the wheel base; note the wheel base is square which helps enable a small turning radius.

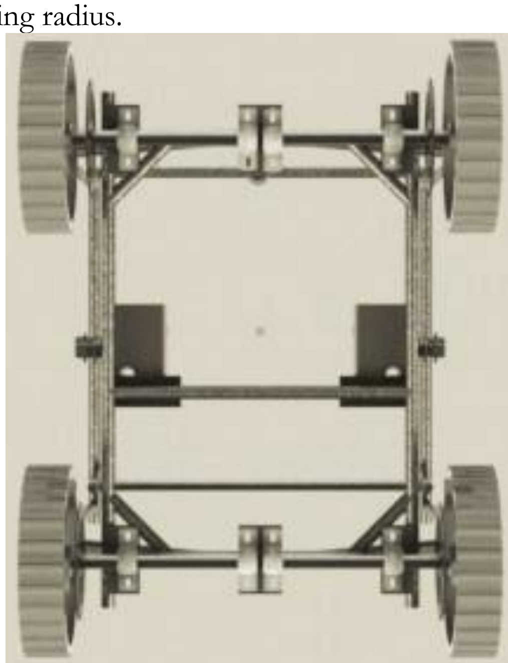

Figure 7: SolidWorks Drawing of Mobility System

Trade-off Assessment

The team considered using tracks instead of wheels. Appendix H shows the trade-off assessment. The team decided that the advantages of the wheels outweighed the advantages of the tracks.

Subsystem Hierarchy

Figure 8 shows the mobility subsystem hierarchy.

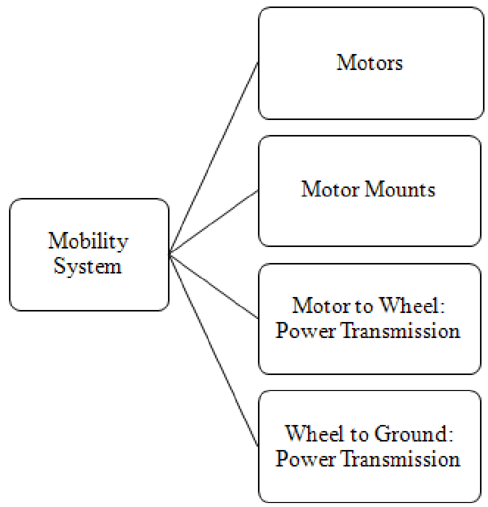

Figure 8: Mobility Subsystem Hierarchy

Design Margins

The mobility system was designed with very large design margins in mind. For example, the drive motors used for the system were the largest we could purchase and stay within our mass and financial limitations. If all of the mass of the loaded Lunabot is placed on one wheel, the axle shaft still has a safety factor of 1.9. The wheels are operating at a 1:6 gear ratio from the motors; this allows for extreme torque and power at low operating speeds.

Risk Assessment

A complete risk analysis can be found in Appendix I, the most critical and likely risks are shown in Table 6 with the risk mitigation strategies.

Table 6: Risks for Mobility Subsystem

Risk	Mitigation Strategy
Wheels lose traction	Careful driving
Not able to maneuver around obstacles	Careful maneuvering
Cannot turn	Careful driving

Verification

The mobility system has been tested on surfaces such as concrete powder, sand and flour. It has proven capable of maneuvering the Lunabot through a mock Lunarena very efficiently. Even when loaded to the maximum weight of 180kg, the mobility system has still been able to perform straight line movement and turns. The system has also been tested against the effects of abrasive material such as dust and concrete powder and has proven to be impervious to all foreign material.

Reliability

The team tested the mobility system integrated with the frame in a sand volleyball court and found the system to be reliable in all test runs. The mobility system has proven capable of all maneuvers necessary for competition. The drive motors recycled from last year's robot began to show signs of wear from previous use so the team purchased new drive motors to ensure reliability. The previous motors are still functional and the team will keep them as back up motors for competition.

Excavation Subsystem

Concept of Operations

Once the Lunabot reaches the excavation zone, the excavation subsystem must excavate the regolith, moving it from the Lunarena ground to a storage system onboard the Lunabot. The excavation system must not alter the regolith in any way.

Interfaces

The excavation subsystem interfaces with the frame system where is it attached. The excavation motor receives control signals from the control subsystem in the form of serial data signal to the speed controller and pulse width modulation to the collector motor. The motor receives power from the power subsystem with 12 Volts and a current of 14 Amps. The linear actuator for the excavation system receives signals from the control system allowing 12 Volts with a current of 2.5 Amps to activate the linear actuator.

Requirements

The main objective of this competition is for the Lunabot to excavate lunar regolith simulant. From this objective, the team created the excavation subsystem. Table 7 shows the driving requirements for the excavation subsystem.

Table 7: Excavation Subsystem Requirements

Requirement	Basis
Excavate 100 kg regolith in 6 minutes	Concept of operations and system requirement P.1
Capable of encountering small rocks up to 1cm in diameter	NASA rules
Not reduce ground clearance of vehicle while traversing obstacle zone	System requirement F.7
Weigh less than 18.6kg	Mass budget

Basis of Design

The team calculated the size of the buckets on the conveyor chain based on the density of the simulant given to the team by NASA as well as calculations accounting for losses between the excavation and the storage bin. The team also calculated the speed of the conveyor based on the requirement of excavating 100kg of simulant within 6 minutes based on our concept of operations as well as the speed necessary to pitch the simulant into the storage bin.

The team considered many options for the excavation subsystem, including a large scoop, horizontal or vertical auger, conveyor, and collection wheel. After comparing each design option to the requirements, all of the design options would not stand up to the requirement of handling small rocks except for the large scoop, conveyor and large wheel. The large wheel is more complex and was not considered further.

Trade-off Assessment

Appendix J shows the trade study between the large scoop and conveyor designs. From this the team found the conveyor belt was the best option because of interface requirements. For the frame and mobility system, our center of gravity would be less affected using the conveyor design. It also requires less current because it moves smaller loads at a time; the large scoop requires more current when collecting a large load.

Subsystem Hierarchy

Figure 9 shows the product hierarchy for the excavation subsystem.

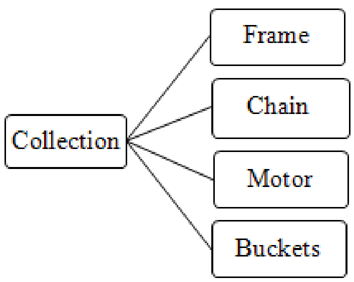

Figure 9: Excavation Product Hierarchy

Design Margins

We designed the excavation system with a large design margin to account for loss of regolith from the collection system. The collection system is capable of excavating 100kg of regolith in 5 minutes, even if only 25% of the theoretical regolith collected reaches the bin.

Risk Assessment

Table 8: Excavation Subsystem Risks

Risk	Mitigation Strategy
Excavation chain jumps sprocket	Proper chain tension
Excavation chain, individual chains become unsynchronized	Keep chain tight Proper chain testing
Simulant too condensed to collect	Visual guides to ensure collecting regolith, move to alternate location and excavate less dense simulant
Natural vibrations shake regolith out of scoops en route to bin	Optimize speed of excavation motor during competition testing days

Verification

The excavation system has been tested in materials such as sand, concrete powder, and flour. This system has proven capable of depositing the required amount of regolith in the bin.

Reliability

The system has also proven robust, having suffered no major mechanical breakdowns in 20 hours of testing. One example of designing for reliability is that we designed the paddles such that one paddle is capable of withstanding all of the force due to the excavation motor running at full speed and power.

Storage/Ejection Subsystem

Concept of Operations

As regolith is excavated, it will fall into a storage bin. After the bin is filled to the desired mass or excavating time has expired, the Lunabot will traverse back across the Lunarena to the hopper for ejection of regolith. At this point the ejection subsystem will eject the regolith from the Lunabot into the hopper located 1m off the Lunarena surface.

Subsystem Hierarchy

Figure 10 shows the storage/ejection product hierarchy.

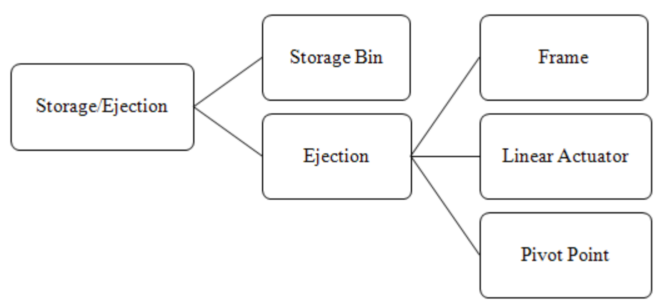

Figure 10: Storage/Ejection Product Hierarchy

Interfaces

The storage/ejection subsystem attaches to the frame. The linear actuator for ejection receives signals from the control system allowing 12 Volts with a current of 10 Amps from the power subsystem to activate the actuator.

Requirements

Once the simulant is collected it must be carried back through the obstacle zone and be put in the hopper located 1m off the surface of the Lunarena. Table 9 shows the driving requirements for the storage/ejection subsystem.

Table 9: Storage/Ejection Subsystem Requirements

Requirement	Basis
Hold 100 kg of simulant of density 1 g/cm^3	System requirement P.1 and the least dense simulant
Capable of depositing regolith into hopper 1.1 meter above surface within 1 minute	System requirement F.2
Weigh less than 14 kg	Mass budget

Trade-off Assessment

The team considered the following design options for ejecting the regolith from the storage bin: raising the bin vertically, raising the bin diagonally, an elevated hopper, a moderately elevated hopper with pivot point, or an ejection conveyor chain. The team performed a trade study shown in Appendix K. Based on this trade study, the team chose the moderately elevated hopper with pivot point.

The storage/ejection subsystem meets the system requirements F.2 and P.1. This design allows for a simpler design for ejection than raising the bin vertically or diagonally and is less complex and more efficient in mass and time than the ejection conveyor chain design.

Basis of Design

The shape of the collection bin is based on the interface between the frame and the storage/ejection system. The bin must fit within the frame and never exceed 2m in height when the regolith is being ejected. The size of the bin was based on the worst case scenario of the simulant being the least dense and the requirement of holding 100kg. The team decided to use 7075 aluminum sheeting to create the bin and aluminum adhesive tape to seal the bin.

Design Margins

Because the team wishes to collect 100kg of regolith, the storage system was designed to be capable of retaining that amount. The bin is designed and constructed for a worst case scenario: a situation in which the regolith has a density of only ——. By designing for this case, the team is assured to have enough capacity to hold 100kg.

Risk Assessment

Table 10: Storage/Ejection Subsystem Risks

Risk	Mitigation Strategy
Regolith fails to exit collection bin	Operator can use the mobility system to shake simulant out. Testing at the competition will inform the team if this will be necessary.

Verification

The system has been tested with materials such as sand, flour, and concrete powder. It has proven capable of retaining and ejecting loads in excess of 100 kg. The collection bin has been completely sealed and does not allow for any material leakage. The Ejection system is capable of placing the bin at an angle in excess of 70 degrees to the vertical, ensuring that all material leaves the bin.

Reliability

The team tested the storage/ejection subsystem with flour and concrete powder similar to the simulant multiple times. The system has stored and ejected the required amount of materials every time.

Power

Concept of Operations

The power system's main requirement is to provide adequate power for the communications, control, excavation, and drive systems during the entire 15 minute competition time. A more accurate representation of this process is shown through the Concept of Operations for the entire system in Table 2 on page 8 and in the power budget shown in Appendix D. Throughout the system operation, communications and control subsystems need to be powered. While the Lunabot is excavating, the power system needs to power the drive motors enough to creep along the mining area while the payload of regolith is increasing. The excavation and the mobility system will be powered simultaneously while in the mining zone. The power system then will power the Lunabot as it traverses the obstacle and dump areas where it will power an ejection system to dump the collected regolith. The power system will run any linear actuator as needed to lift and lower the excavation belt.

Interfaces

The power subsystem is required to provide power to all on-board subsystems. It must drive the mobility, excavation, and ejection subsystems as well as provide power for the on-board communications and control subsystem components.

Requirements

Table 11 shows the driving requirements for the power subsystem and the basis of these requirements.

Table 11: Power Subsystem Requirements

Requirement	Basis
Batteries must provide specified voltage and current to all Lunabot components for 30 minutes	System requirement: F.6, V.3
Weigh less than 8kg	Mass budget
Contain large red push button that deactivates all power onboard the Lunabot	Competition rules

Basis of Design

Testing last year's Lunabot, the team found power requirements for the electromechanical systems. Appendix L shows the power consumption calculations from testing. The team based their design on these calculations as well as energy per unit mass ratio.

Trade-off Assessment

The team considered two different design options. The first was a two battery system with all 24 Volt components connected to one battery and all 12 Volt components connected to a different battery. Using this system, the communications and control subsystems on the Lunabot would be connected to the same battery as high power excavation components. The team chose instead to use a three battery subsystem with one 24 Volt battery and two 12 Volt batteries, thereby isolating the control and communications components from the electromechanical components. This design isolates high power components from the communication and control components; ensuring reliable voltage levels for the critical control electronics. The team felt this was a good trade off of reliability and mass.

The next design challenge for the team regarding the power system was what type of batteries to use. The team seriously considered lead acid, NiMH and lithium ion batteries. Based on the trade study shown in Appendix M we chose lithium ion batteries and their superior energy to mass ratio.

Subsystem Hierarchy

Figure 11 shows the product hierarchy for the power subsystem.

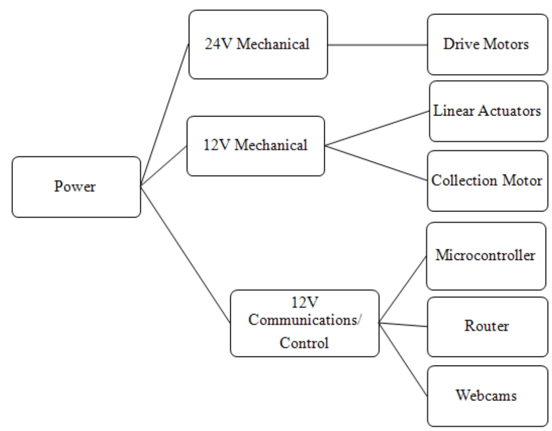

Figure 11: Power Product Hierarchy

Design Margins

We made all energy calculations using 30 minutes for the competition time instead of the actual 15 minutes. This gives a safety factor of two. The team designed for worst case scenario by estimating power consumption from power consumption measured from last year's robot during sand pit testing. Power consumption for the mobility system took into account an increasing load as regolith is collected.

Risk Assessment

Table 12 shows the critical risk of the power subsystem and a mitigation strategy. See Appendix I for a complete list of risks.

Table 12: Power Subsystem Risks

Risk	Mitigation Strategy
Connections coming lose	Connections will be securely attached and strain reliefs will be installed.

in power subsystem	During testing, these connections will be monitored to make sure they stay intact.

Verification

The power subsystem has been tested and meets our system requirement V.3. We found the power subsystem provides power to the Lunabot for 45 minutes for continuous communication and control operation. The batteries adequately provide power to the mobility, excavation, ejection and control/communication subsystems.

Reliability

During testing the only failure has been at connection points. The team has optimized the connections by replacing detachable connection with permanent connections.

Control Subsystem

Concept of Operations

The control system needs to receive commands from the command center sent through a TCP/IP network. It will then need to send control signals to the motors and linear actuators and other devices based on those instructions allowing full remote control of the Lunabot while it is in the Lunarena. Third, the control system will use various incorporated sensors to capture information about the Lunabot and the Lunarena's environment. Finally, the system will relay the data from the sensors back to the command center through NASA's network so that the operators can monitor the progress of the Lunabot and control it appropriately.

Subsystem Hierarchy:

Figure 12 shows the product hierarchy for the control subsystem.

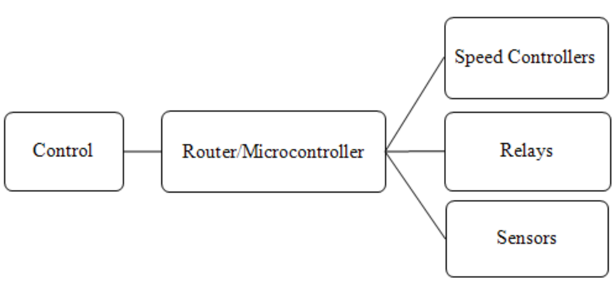

Figure 12: Control Product Hierarchy

Basis of Design

We designed the control subsystem based on the overall system requirements as well as testing performed on the JBU 2010 Lunabot. An Arduino Mega microcontroller with an attached Ethernet shield was used as the onboard computer because it was a compact, lightweight, and low cost board with plenty of input and output pins to interface with the system components.

Interfaces

Since the control subsystem is essentially the brain on-board the Lunabot, it interfaces with all electromechanical components. Appendix N shows these interfaces.

Requirements

Table 13: Control Subsystem Requirements

Requirement	Basis
Capable of independently controlling 2 DC drive motors with variable forward and reverse speeds	System requirement: F.7 and mobility interface
Capable of controlling 1 DC excavation motor with variable speeds in one direction	System requirement: F.1 and excavation interface
Capable of independently controlling 2 DC linear actuators in forward and reverse	System requirement: F.1, F.2, F.7 and excavation interface and ejection interface
Capable of monitoring the Lunabot's status and the immediate surroundings through sensors	System requirement: F.6, I.1, O.1, O.2

Design Margins

Since the largest linear actuator was rated for 10 Amps, 30 Amps rated relays were used to drive the linear actuators while providing a large margin. The peak current of the drive motors was measured to be 20 Amps. Therefore, Sabertooth 2x25 Speed Controllers rated at 25 Amps continuous and 50 Amps peak per channel were used to control the drive motors and excavation motor. Using identical relays and speed controllers for all linear actuators and motors reduced the complexity of the system by limiting the number of unique parts, and made it easier to acquire spare parts.

Trade-off Assessment

The main component for the control subsystem is the microcontroller; therefore the most crucial design decision for the subsystem was what microcontroller to use.

The 2010 team built a remote controlled system using the MakeController Kit. The current team dismissed the possibility of reusing their control system because the controller did not function reliably and there were critical bugs in the firmware. The team then considered three main options: SPA protocol, The Gumstix[b] controller, and the Arduino microcontroller board.

The team performed a trade-off assessment found in Appendix O. Based on the result of this study, the team chose to use the Arduino microcontroller. The main issue with SPA is that each sensor module would require a dedicated microcontroller to serve as the SPA compliant interface with the main controller, adding to the complexity and cost of the control subsystem. The main deterrent from the Gumstix controller was the expense of the option. The team chose the Arduino microcontroller because it is cheaper than the Gumstix computer and is still easily interfaces with sensors.

Risk Assessment

Table 14 shows the most likely and devastating risks and the steps taken to account for these risks.

Table 14: Control Subsystem Risk Assessment

Risk	Mitigation Strategy
Electro static discharge destroys microcontroller preventing control	The microcontroller will be enclosed, grounded and teammates will wear anti static wrist straps while handling the microcontroller
Overheating microcontroller from dust preventing control	An enclosure for the microcontroller will be designed
Short circuit due to vibration preventing control	Every connection secured and make sure the wires cannot vibrate against the frame

Verification

Each component in the control system was first individually tested to ensure that it was working correctly. Next the components were connected to each other one at a time and the interfaces between the components were tested to ensure full functionality. This was done on a "flat robot," i.e. nothing connected to the robot frame as Figure 13 shows.

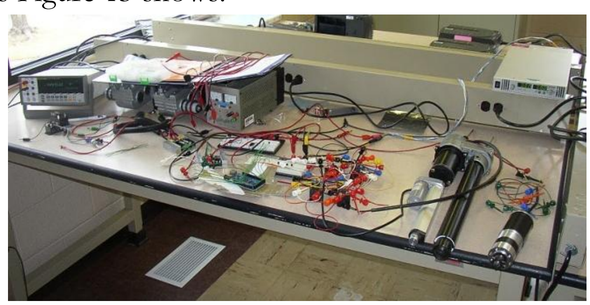

Figure 13: Flat Robot Testing

The system components were then interfaced with the motors and linear actuators and those interfaces were tested. Also, the control computer was interfaced with the communications network and that interface was tested to ensure that the on-board computer reliably received incoming commands. Testing on the mechanical subsystems verified that the

[b] http://www.gumstix.com/

control subsystem meets its subsystem and system requirements.

Reliability

After each component interface had been tested, the whole control system was assembled and the system was tested to determine that all components were functioning reliably without interference. Finally, the control system was integrated with the other sub-systems of the Lunabot and the Lunabot was tested for full functionality and reliability. Figure 14 shows the control system ready for mounting on the Lunabot frame.

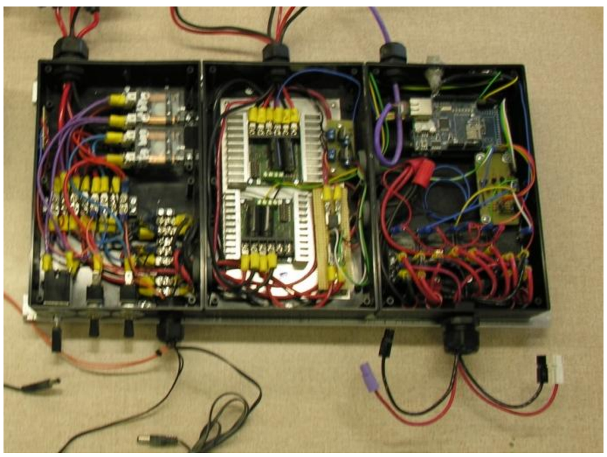

Figure14: Control System

Communications

Concept of Operations

The communications system will take user control inputs via an X-Box controller. These inputs are fed to a communication program located on the control laptop where they are interpreted and then sent via LAN connection to communication devices onboard the Lunabot. Appendix P shows a complete communication system diagram.

Interfaces

The communications system is a system created to effectively interface between the operator and the control system. The operator interfaces with the communications system via an X-Box controller. The communications system takes this information and sends it to the microcontroller through a router. Cameras are mounted on the frame and connected to the router as well.

Requirements

Table 15 shows the driving requirements for the communications subsystem

Table 15: Communication Subsystem Requirements

Requirement	Basis
Operator isolated from the robot during excavation	System requirement: F.6
The average bandwidth must be less than 5 mbps	System requirement: F.5
User control system must have ability to handle up to 3 variable speed outputs	Mobility interface

Trade-off Assessment

The team considered several options for the user interface: X-Box controller, joystick, keyboard or autonomous (eliminating the user interface completely). Appendix Q shows the trade-off assessment that led to the team choosing to use an X-Box controller. The team found that an X-Box controller combined the advantages of the joystick and keyboard in one device familiar to the operator. Complexity and desire to perform very well in the competition eliminated an autonomous robot.

Basis of Design

The communications subsystem meets the system requirement F.6, system operable from alternate location. The design of the communications subsystem is to create a user interface that lends to an easily operated Lunabot.

Subsystem Hierarchy

Figure 15 shows the product hierarchy for the communications subsystem.

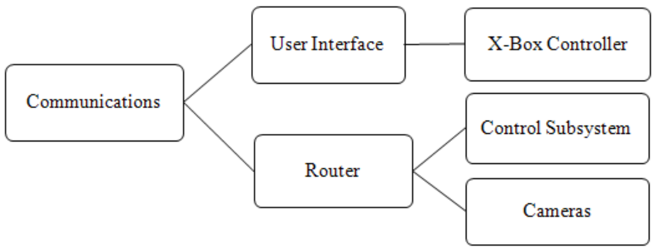

Figure 15: Communications Product Hierarchy

Design Margin

Based on testing the camera from the 2010 JBU Lunabot, the communications system requires 1.4 MBps for each camera and the amount of bandwidth used by the microcontroller can be treated as negligible. We designed the communications system to use no more than three cameras. Therefore the design calls for 4.2 MBps on leaving 0.8 MBps margin.

Risk Assessment

None of the risks of the Communication subsystem ranked in the critical zone of the risk analysis; Appendix I shows a complete risk analysis.

Verification

We tested the communications and control interface by sending commands from the computer to the Arduino board connected by Ethernet cable. Next, we tested the interface by sending commands from the computer to a router connected to the Arduino board. After finding this test successful, we tested using a two router system with one router connected to the laptop and one on the Lunabot connected to the Arduino. After integrating the communications and control subsystems with the mechanical subsystems testing revealed an unacceptable intermittent time delay of over one second. We modified the laptop program to send a data packet only when an input was changed on the Xbox controller. We also added a 0.05s delay between sending commands to adjust for the lower processing speed of the Arduino compared to the laptop. These modifications worked and prevent the Arduino from being overloaded with commands.

Reliability

After making changes during the verification process, the communications and control interface was found to be reliable after numerous tests. To date it has undergone 90 hours of testing.

Requirement Flow-Down to Validation Check Out

For each subsystem, the subsystem requirements are based on the system requirements. Each component chosen for the design is based on the subsystem requirements. As the team manufactured the design, each component was tested to meet the subsystem requirement and therefore the system requirements. As the components were found to meet requirements, they were integrated into the subsystems. As the subsystems were found to meet requirements, they were integrated into the system as a whole.

The team added functionality to the system one subsystem at a time. The team began system integration by integrating communications with control. This interface was then tested. The power system was then added so that the entire electrical system was integrated. Simultaneously, the frame was created and tested. The mobility system was then integrated with the frame and tested. At this point, the electrical and mechanical systems were integrated and tested. Next, the storage and ejection system were integrated into the system and tested. Finally, the collection subsystem was integrated into the system as a whole and tested. After complete system integration the system has undergone system level testing.

Due to the amount of component level testing and subsystem level testing, integration went smoothly and the system operated as designed. Since full system integration, the only change necessary has been adding a delay in the communications system to enable the control system to keep up with the user commands.

System Integration

As stated in the previous section, the team did testing from component level testing all the way to system testing. For example, we have applied a 100 kg load and tested the maneuverability. The team tested the robot by collecting both concrete powder and flour.

Use of Systems Life Cycle

The team applied the systems life cycle shown in Figure 3 not only to the system as a whole but to each subsystem. Appendix R shows the schedule for the design process. This schedule facilitated the use of the systems life cycle during the design process.

Configuration Management

The process of monitoring system progress is defined as configuration management. Since most design work and testing was created and documented on the computer, the most effective way of organizing and communicating design information was to create a shared folder accessible by all team members. The team used the online folder to monitor system progress. All team members and the faculty advisor have access to the folder. The folder was divided into folders for each subsystem, with a folder for testing plans and testing results for all subsystems as well as a budget folder. Each team member is responsible for documenting design in their subsystem folders, and recording subsystem testing results and actual budget usage.

The online folder was backed up routinely. These backups provided one level of version archiving. Also throughout the design process, working versions of files were archived.

Project Management

Similar to a real world project, the project followed a management system shown in Figure 16.

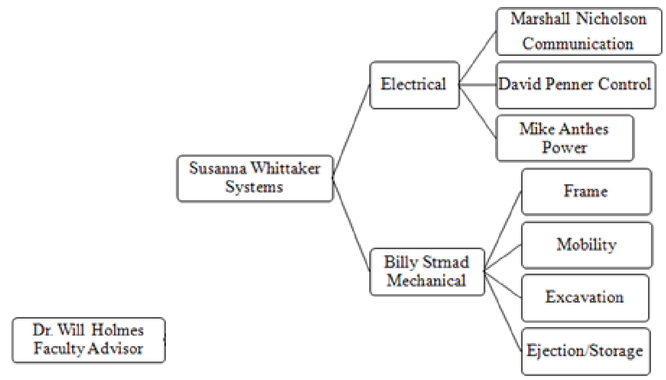

Figure 16: Project Management

Budget

As with any project, the team was constrained by financial resources. The team received grants from NASA, the Arkansas Space Consortium and JBU. Appendix S shows the team's budget of $8,500.

Conclusion

As of this paper's submission date, the JBU Lunabot is undergoing competition style full system testing. All testing to date indicated the robot will excavate the required 10 kg of simulant and there is a good chance it will excavate around 100 kg of simulant. This functionality was enabled by a systems engineering approach, teamwork, system design, well defined interfaces, and testing at component/subsystem level. The team looks forward to the competition.

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Appendix A: Lunabotics Mining Competition Rules

NASA's Lunabotics Mining Competition

2011 Rules & Rubrics

November 23, 2010

Kennedy Space Center, Florida

Introduction

NASA's Lunabotics Mining Competition is designed to promote the development of interest in space activities and STEM (Science, Technology, Engineering, and Mathematics) fields. The competition uses excavation, a necessary first step towards extracting resources from the regolith and building bases on the moon. The unique physical properties of lunar regolith and the reduced 1/6th gravity, vacuum environment make excavation a difficult technical challenge. Advances in lunar regolith mining have the potential to significantly contribute to our nation's space vision and NASA space exploration operations. The competition will be conducted by NASA at Kennedy Space Center. The teams that can use telerobotic or autonomous operation to excavate the most lunar regolith simulant within a 15-minute time limit will win the competition. The minimum excavation requirement is 10.0 kg, and the excavation hardware mass limit is 80.0 kg. Winners are eligible to receive first, second, or third place awards of $5,000, $2,500, and $1,000, respectively.

Undergraduate and graduate student teams enrolled in a U.S. or international college or university are eligible to enter the Lunabotics Mining Competition. Design teams must include: at least one faculty with a college or university and two or more undergraduate or graduate students. Teams will compete in up to five categories including: on-site mining, systems engineering paper, outreach project, slide presentation (optional), and team spirit (optional). Additionally, teams can earn bonus points toward the Joe Kosmo Award for Excellence multidisciplinary teams and collaboration between a majority and U.S. minority serving institutions earn. All documents must be submitted in English.

Awards include monetary scholarships, a school trophy or plaque, individual certificates, KSC launch invitations, and up to $1,500 travel expenses for each team member and one faculty advisor to participate with the NASA Desert RATS as the winners of the Joe Kosmo Award for Excellence. Award details are available at www.nasa.gov/lunabotics.

The Lunabotics Mining Competition is a student competition that will be conducted in a positive professional way. So this is a reminder to be courteous in your correspondence and on-site at the competition because unprofessional behavior or unsportsmanlike conduct will not be tolerated and will be grounds for disqualification.

Game Play Rules

1) These rules and specifications may be subject to future updates by NASA at its sole discretion.

2) Teams will be required to perform 1 official competition attempt using lunar regolith simulant, Lunarena and collector provided by NASA. NASA will fill the Lunarena with compacted lunar regolith simulant that matches as closely as possible to the lunar regolith described in the Lunar Sourcebook: A User's Guide to the Moon, edited by G. H. Heiken, D. T. Vaniman, and B. M. French, copyright 1991, Cambridge University Press. NASA will randomly place 3 obstacles and create 2 craters on each side of the Lunarena. Each competition attempt will occur with 2 teams competing at the same time, 1 on each side of the Lunarena. After each competition attempt, the obstacles will be removed, the lunar regolith simulant will be returned to a compacted state, and the obstacles will be returned to the Lunarena. See the Lunarena Diagrams on page 7.

3) In the official competition attempt, the teams that acquire (and deliver into the collector container) the first, second, and third most mass by excavating lunar regolith simulant over the minimum excavation requirement (10 kg) within the time limit (15 minutes) will respectively win first, second, and third place awards. In the case of a tie, the teams will compete in a head-to-head round, where the team that acquires the most lunar regolith simulant in that round wins.

4) All excavated mass deposited in the collector during the official competition attempt will be weighed after completion of the competition attempt. Any obstacles deposited in the collector will be removed from the lunar regolith simulant collected.

5) The excavation hardware shall be placed in the randomly designated starting zones. The order of teams will be randomly chosen throughout the competition.

6) A team's excavation hardware shall only excavate lunar regolith simulant located in that team's respective mining zone at the opposite end of the Lunarena from the team's starting zone. The team's exact starting point and traversal direction will be randomly selected immediately before the competition attempt.

7) The excavation hardware is required to move across the obstacle zone to the mining zone and then move back to the collector box to deliver the simulant into the collector box. See the Lunarena Diagrams on page 7.

8) Each team is responsible for placement and removal of their excavation hardware onto the lunar regolith simulant surface. There must be 1 person per 23 kg of mass of the excavation hardware, requiring 4 people to carry the maximum allowed mass. Assistance will be provided if needed.

9) Each team is allotted a maximum of 10 minutes to place the excavation hardware in its designated starting position within the Lunarena and 5 minutes to remove the excavation hardware from the Lunarena after the 15-minute competition attempt has concluded.

10) The excavation hardware operates during the 15-minute time limit of the competition attempt. The 15-minute time limit will be reduced if a team is not ready at the team's competition attempt start time. Time will start even if a team is still setting up their excavator after the 10 minute setup time period has elapsed. The competition attempt for both teams in the Lunarena will end at the same time.

11) The excavation hardware will end operation immediately when the power-off command is sent, as instructed by the competition judges.

12) The excavation hardware cannot be anchored to the lunar regolith simulant surface prior to the beginning of the competition attempt.

13) Each team will be permitted to repair or otherwise modify the excavation hardware after the team's practice time. The excavation hardware will be inspected the evening before the competition takes place and quarantined until just before the team's competition attempt. Batteries will not be quarantined and may continue to charge.

Field Rules

14) At the start of the competition attempt, the excavation hardware may not occupy any location outside the defined starting zone. At the start of each competition attempt the starting location and direction will be randomly determined.

15) The collector box top edge will be placed so that it is adjacent to the side walls of the Lunarena without a gap and the height will be approximately 1 meter from the top of the simulant surface directly below it. The collector top opening will be 1.65 meters long and .48 meters wide. See the Lunarena Diagrams on page 7. A target may be attached to the collector for navigation purposes only. This navigational aid must be attached during the setup time and removed afterwards during the removal time period. The mass of the navigational aid is included in the maximum excavation hardware mass limit of 80.0 kg and must be self-powered.

16) There will be 3 obstacles placed on top of the compressed lunar regolith simulant surface within the obstacle zone before the competition attempt is made. The placement of the obstacles will be randomly selected before the start of the competition attempt. Each obstacle will have a diameter of approximately 20 to 30 cm and an approximate mass of 7 to 10 kg. Obstacles placed in the collector will not be counted as part of the excavated mass. There will be 2 craters of varying depth and width, being no wider or deeper than 30cm. No obstacles will be intentionally buried in the simulant by NASA, however, simulant includes naturally occurring rocks.

17) Excavation hardware must operate within the Lunarena: it is not permitted to pass beyond the confines of the outside wall of the Lunarena and the collector during the competition attempt. The regolith simulant must be collected in the mining zone allocated to each team and deposited in the collector. The team may only dig in its own mining zone. The simulant must be carried from the mining zone to the collector by any means. The excavator can separate intentionally, if desired, but all parts of the excavator must be under the team's control at all times. Any ramming of the wall may result in a safety disqualification at the discretion of the judges. A judge may disable the excavator by pushing the red emergency stop button at any time.

18) The excavation hardware must not push lunar regolith simulant up against the wall to accumulate lunar regolith simulant.

19) If the excavation hardware exposes the Lunarena bottom due to excavation, touching the bottom is permitted, but contact with the Lunarena bottom or walls cannot be used at any time as a required support to the excavation hardware. Teams should be prepared for airborne dust raised by either team during the competition attempt.

Technical Rules

20) During the competition attempt, excavation hardware is limited to autonomous and telerobotic operations only. No physical access to the excavation hardware will be allowed during the competition attempt. In addition, telerobotic operators are only allowed to use data and video originating from the excavation hardware. Visual and auditory isolation of the telerobotic operators from the excavation hardware in the Mission Control Room is required during the competition attempt. Telerobotic operators will be able to observe the Lunarena through fixed overhead cameras on the Lunarena through monitors that will be provided by NASA in the Mission Control Room. These monitors should be used for situational awareness only. The Lunarena will be outside in an enclosed tent.

21) Mass of the excavation hardware shall not exceed 80.0 kg. Subsystems on the excavator used to transmit commands/data and video to the telerobotic operators are counted towards the 80.0 kg mass limit. Equipment not on the excavator used to receive commands from and send commands to the excavation hardware for telerobotic operations is excluded from the 80.0 kg mass limit.

22) The excavation hardware must be equipped with an easily accessible red emergency stop button (kill

switch) of minimum diameter 5 cm on the surface of the excavator requiring no steps to access. The emergency stop button must stop excavator motion and disable all power to the excavator with 1 push motion on the button.

23) The communications rules used for telerobotic operations follow:

A. LUNABOT WIRELESS LINK

1. Each team will provide the wireless link (access point, bridge, or wireless device) to their Lunabot

a. KSC will provide an elevated network drop (Female RJ-45 Ethernet jack) in the Lunarena that extends to the control room, where we will have a network switch for the teams to plug in their laptops

i. The network drop in the Lunarena will be elevated high enough above the edge of the regolith bed wall to provide adequate radiofrequency visibility of the competition pit.

ii. A shelf will be setup next to the network drop and located 4 to 6 feet off the ground and will be no more than 50 feet from the Lunabot. This shelf is where teams will place their Wireless Access Point (WAP) to communicate with their rover.

iii. The WAP shelves for side A and side B of the regolith pit will be no closer than 25' from each other to prevent electromagnetic interference (EMI) between the units.

b. NASA will provide a standard 110VAC outlet by the network drop. Both will be no more than 2 feet from the shelf.

c. During setup time before the match starts the teams will be responsible for setting up their access point.

2. The teams must use the USA IEEE 802.11 b/g standard for their wireless connection (WAP and rover client) Teams cannot use multiple channels for data transmission. Encryption is not required but it is highly encouraged to prevent unexpected problems with team links.

a. During a match, one team will operate on channel 1 and the other team will operate on channel 11.

b. The channel assignments will be made either upon check-in or a few weeks prior to the event.

3. Each team will be assigned an SSID that they must use for their wireless equipment.

a. SSID will be "Team_##"

b. Teams shall broadcast their SSID

4. Bandwidth constraints:

a. There will not be a peak bandwidth limit.

b. Teams will be awarded in some way for using the least amount of total bandwidth during the timed and NASA monitored portion of the competition.

c. The communications link is required to have an average bandwidth of no more than 5 megabits per second.

B. RF & COMMUNICATIONS APPROVAL

1. There will be a communications judge's station where each team will have approximately 15 minutes to show the judges that their Lunabot & access point is operating only on their assigned channel.

2. To successfully pass the communications judge's station a team must be able to command their Lunabot (by driving a short distance) from their Lunabot driving/control laptop through their wireless access point. The judges will verify this and use the appropriate monitoring tools to verify that the teams are operating only on their assigned channel.

3. If a team cannot demonstrate the above tasks in the allotted time, they will be disqualified from the competition.

4. Each team will have an assigned time on Monday or Tuesday to show the judges their compliance with the rules.

5. The NASA communications team will be available to help teams make sure that they are ready for the judging station on Monday and Tuesday.

6. Once the team arrives at the judge's station, they can no longer receive assistance from the NASA communications team.

7. If a team is on the wrong channel during a match, they will be required to power down and be disqualified from that match.

C. WIRELESS DEVICE OPERATION IN THE PITS

1. Teams will not be allowed to power up their transmitters on any frequency in the pits once the practice matches begin. All teams shall have a hard-wired connection for testing in the pits.
2. There will be designated times for teams to power up their transmitters when there are no matches underway.

24) The excavation hardware must be contained within 1.5m width x .75m length x 2m height. The hardware may deploy beyond the 1.5 m x .75 m footprint after the start of the competition attempt, but may not exceed a 2 meter height. The excavation hardware may not pass beyond the confines of the outside wall of the Lunarena and the collector during the competition attempt to avoid potential interference with the surrounding tent. The team must declare the orientation of length and width to the inspection judge. Because of actual lunar hardware requirements, no ramps of any kind will be provided or allowed.

25) To ensure that the excavation hardware is usable for an actual lunar mission, the excavation hardware cannot employ any fundamental physical processes (e.g., suction or water cooling in the open lunar environment), gases, fluids or consumables that would not work in the lunar environment. For example, any dust removal from a lens or sensor must employ a physical process that would be suitable for the lunar surface. Teams may use processes that require an Earth-like environment (e.g., oxygen, water) only if the system using the processes is designed to work in a lunar environment and if such resources used by the excavation hardware are included in the mass of the excavation hardware.

26) Components (i.e. electronic and mechanical) are not required to be space qualified for the lunar vacuum, electromagnetic, and thermal environments.

27) The excavation hardware may not use any process that causes the physical or chemical properties of the lunar regolith simulant to be changed or otherwise endangers the uniformity between competition attempts.

28) The excavation hardware may not penetrate the lunar regolith simulant surface with more force than the weight of the excavation hardware before the start of the competition attempt.

29) No ordnance, projectile, far-reaching mechanism, etc. may be used (excavator must move on the lunar regolith simulant).

30) No excavation hardware can intentionally harm another team's hardware. This includes radio jamming, denial of service to network, regolith simulant manipulation, ramming, flipping, pinning, conveyance of current, or other forms of damage as decided upon by the judges. Immediate disqualification will result if judges deem any maneuvers by a team as being offensive in nature. Erratic behavior or loss of control of the excavation hardware as determined by the judges will be cause for immediate disqualification.

31) Teams must electronically submit documentation containing a description of the excavation hardware, its operation, potential safety hazards, a diagram, and basic parts list.

32) Teams must electronically submit video documentation containing no less than 30 seconds of excavation hardware operation and at least 1 full cycle of operation. One full cycle of operations includes excavation and depositing material. This video documentation is solely for technical evaluation of the team's excavation hardware.

Video specifications:

Formats/Containers: .avi, .mpg, .mpeg, .ogg, .mp4, .mkv, .m2t, .mov; Codecs: MPEG-1, MPEG-2, MPEG-4 (including AVC/h.264), ogg theora; Minimum frame rate: 24 fps; Minimum resolution: 320 x 240 pixels

Definitions

Black Point-1 (BP-1) - A crushed lava aggregate with a natural particle size distribution similar to that of lunar soil. The aggregate will have a particle size and distribution similar to the lunar regolith as stated in the Lunar Sourcebook: A User's Guide to the Moon, edited by G. H. Heiken, D. T. Vaniman, and B. M. French, copyright 1991, Cambridge University Press. Teams are encouraged to develop or procure simulants based on lunar type of minerals and lunar regolith particle size, shape, and distribution.

Collector - A device provided by NASA for the competition attempt into which each team will deposit excavated regolith simulant. The collector will be large enough to accommodate each team's excavated regolith simulant. The collector will be stationary and located adjacent to the Lunarena. Excavated regolith simulant mass will be measured after completion of the competition attempt. The collector mass will not be counted towards the excavated mass or the mass of the excavation hardware. The collector will be 1.65 meters long and .48 meters wide. The collector walls will rise to an elevation of approximately 1 meter above the BP-1 surface directly below the collector. See the Lunarena Diagrams on page 7.

Competition attempt - The operation of a team's excavation hardware intended to meet all the requirements for winning the competition by performing the functional task. The duration of the competition attempt is 15-minutes.

Excavated mass - Mass of the excavated lunar regolith simulant delivered to the collector by the team's excavation hardware during the competition attempt, measured in kilograms (kg) with official result recorded to the nearest one tenth of a kilogram (0.1 kg).

Excavation hardware - Mechanical and electrical equipment, including any batteries, gases, fluids and consumables delivered by a team to compete in the competition.

Functional task - The excavation of regolith simulant from the Lunarena by the excavation hardware and deposit from the excavation hardware into the collector box.

Minimum excavation requirement - 10.0 kg is the minimum excavated mass which must be met in order to qualify to win the competition.

Power - All power shall be provided by a system onboard the excavator. No facility power will be provided to the excavator. There are no power limitations except that the excavator must be self-powered and included in the maximum excavation hardware mass limit of 80.0 kg.

Practice time - Teams will be allowed to practice with their excavators in the Lunarena. NASA technical experts will offer feedback on real-time networking performance during practice attempts.

Reference point - A fixed location on the excavation hardware that will serve to verify the starting location and traversal of the excavation hardware within the Lunarena. An arrow on the reference point must mark the forward direction of the excavator in the starting position configuration. The judges will use this reference point and arrow to orient the excavator in the randomly selected direction and position.

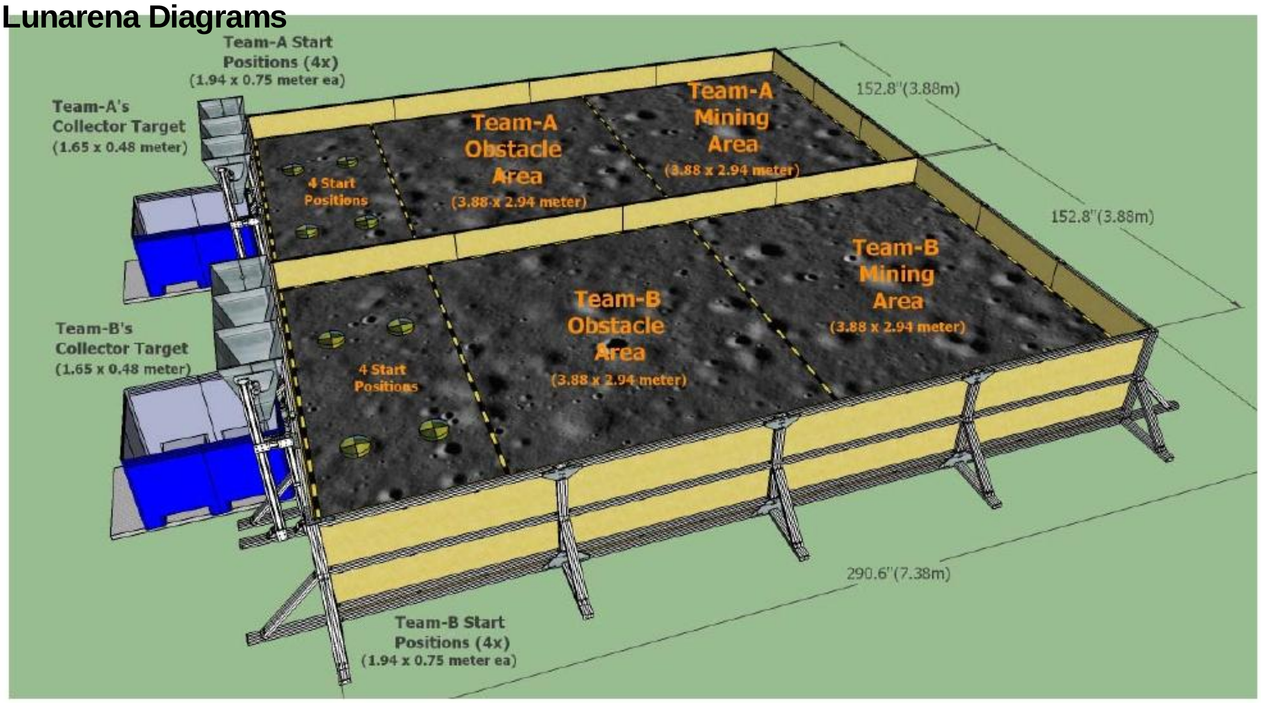
Lunabot - A teleoperated robotic excavator in NASA's Lunabotics Mining Competition.

Lunarena - An open-topped container (i.e., a box with a bottom and 4 side walls only), containing regolith simulant, within which the excavation hardware will perform the competition attempt. The inside dimensions of the each side of the Lunarena will be 7.38 meters long and 3.88 meters wide, and 1 meter in depth. A dividing wall will be in the center of the Lunarena. The Lunarena for the official practice days and competition will be provided by NASA. See the Lunarena Diagrams on page 7.

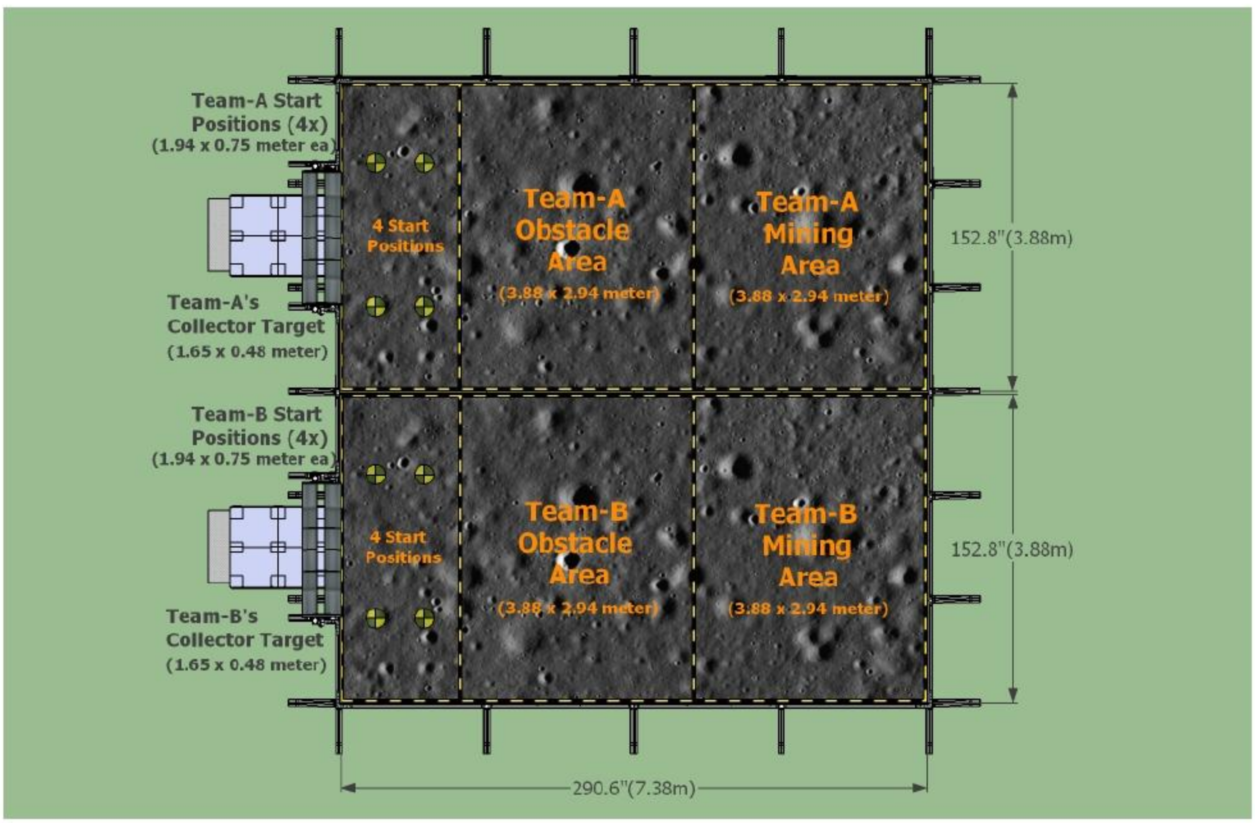
Telerobotic - Communication with and control of the excavation hardware during the competition attempt must be performed solely through the provided communications link which is required to have a total bandwidth of no more than 5.0 megabits/second on all data and video sent to and received from the excavation hardware.

Time Limit - The amount of time within which the excavation hardware must perform the functional task, set at 15 minutes; set up excavation hardware, set at 10 minutes; and removal of excavation hardware, set at 5 minutes.

Lunarena Diagrams



Lunarena Diagram (side view)



Lunarena Diagram (top view)

Lunabotics Systems Engineering Paper

Each team must submit a Systems Engineering Paper electronically in PDF by April 18, 2011. Cover page must include: team name, title of paper, full names of all team members, university name and faculty advisor's full name. Appendices are not included in the page limitation and the judges are not obligated to consider lengthy appendices in the evaluation process. A minimum score of 15 out of 20 possible points must be achieved to qualify to win in this category. In the case of a tie, the judges will choose the winning Systems Engineering Paper. The judges' decision is final. The team with the winning Systems Engineering Paper will receive a team plaque, individual certificates, and a $500 scholarship.

Lunabotics Systems Engineering Paper Scoring Rubric

Elements	4	3	2	1
Content: • Formatted professionally, clearly organized, correct grammar and spelling, 10 - 15 pages; 12 font size; single spaced. • Cover page • Introduction • Purpose • Sources	All five elements are clearly demonstrated	Four elements are clearly demonstrated	Three elements are clearly demonstrated	Two or less elements are clearly demonstrated
Intrinsic Merit: • Deliverables identified • Budget • Schedule • Major reviews: system requirements, preliminary design and critical design • Illustrations support the technical content	All five elements are clearly demonstrated	Four elements are clearly demonstrated	Three elements are clearly demonstrated	Two or less elements are clearly demonstrated
Technical Merit: • Concept of operations • System Hierarchy • Basis of design • Interfaces defined • Requirements definition • Design margins • Trade-off assessment • Risk assessment • Reliability • Verification • Requirement flow-down to validation and checkout • Use of system life cycle	One point for each element clearly demonstrated up to twelve points.			

Lunabotics Outreach Project

All teams must participate in an educational outreach project. Outreach examples include actively participating in school career days, science fairs, technology fairs, extracurricular science or robotic clubs, or setting up exhibits in local science museums or a local library. Other ideas include organizing a program with a Boys and Girls Club, Girl Scouts, Boy Scouts, etc. Teams are encouraged to have fun with the outreach project and share knowledge of science, robotics and engineering with the local community.

Each team must submit a report of the Lunabotics Outreach Project electronically in PDF by April 18, 2011. Cover page must include: team name, title of paper, full names of all team members, university name and faculty advisor's full name. A minimum score of 15 out of 20 possible points must be achieved to qualify to win in this category. In the case of a tie, the judges will choose the winning outreach project. The judges' decision is final. The team with the winning outreach project will receive a team plaque, individual certificates, and a $500 scholarship.

Lunabotics Outreach Project Scoring Rubric

Elements	4	3	2	1
Content: • Introduction • Outreach recipient group identified • Purpose • Cover page	All four elements are clearly demonstrated	Three elements are clearly demonstrated	Two elements are clearly demonstrated	One element is clearly demonstrated
Educational Outreach: • Inspires others to learn about robotics, engineering or lunar activities • Engages others in robotics, engineering or lunar activities • Utilizes hands-on activities	All three elements are clearly demonstrated	Two elements are clearly demonstrated	One element is clearly demonstrated	No elements are clearly demonstrated
Creativity: • Inspirational • Engaging • Material corresponds to audience's level of understanding	All three elements are clearly demonstrated	Two elements are clearly demonstrated	One element is clearly demonstrated	No elements are clearly demonstrated
Illustrations and Media: • Appropriate • Demonstrates the outreach project • Pictures	All three elements are clearly demonstrated	Two elements are clearly demonstrated	One element is clearly demonstrated	No elements are clearly demonstrated
Formatting and Appearance: • Correct grammar and spelling • Five-page limit (cover page and appendices excluded in page count) • Clearly organized	All three elements are clearly demonstrated	Two elements are clearly demonstrated	One element is clearly demonstrated	No elements are clearly demonstrated

Lunabotics Slide Presentation

Must be submitted electronically by April 18, 2011 in PDF. The Lunabotics Slide Presentation is an optional category in the overall competition. A cover slide must contain the team name, title of presentation, full names of all team members, university name and faculty advisor's full name. A minimum score of 15 out of 20 possible points must be achieved to qualify to win in this category. In the case of a tie, the judges will choose the winning presentation. The judges' decision is final. The team with the winning presentation will receive a team plaque, individual certificates, and a $500 scholarship.

Lunabotics Slide Presentation Scoring Rubric

Elements	4	3	2	1
Content: • Cover slide • Introduction • Purpose • Stand alone - presentation will be judged prior to the competition without the benefit of a presenter • Sources referenced	All five elements are clearly demonstrated	Four elements are clearly demonstrated	Three elements are clearly strated demon	Two or less elements are clearly demonstrated
Technical Merit: • Final Lunabot design • Design process • Design decisions • Lunabot functionality • Safety features • Special features	All six elements are clearly demonstrated	Five elements are clearly demonstrated	Four elements are clearly strated demon	Two or less elements are clearly demonstrated
Creativity: • Innovative • Inspirational • Engaging	All three elements are clearly demonstrated	Two elements are clearly demonstrated	One element is clearly strated demon	No elements are clearly demonstrated
Illustrations and Media: • Appropriate • Supports the technical content • Shows progression of project • Clearly presents design of excavator	All four elements are clearly demonstrated	Three elements are clearly demonstrated	Two elements are clearly strated demon	One element is clearly demonstrated
Formatting and Appearance: • Proper grammar • Correct spelling • Readable • Aesthetically pleasing	All four elements are clearly demonstrated	Three elements are clearly demonstrated	Two elements are clearly strated demon	One element is clearly demonstrated

Lunabotics Team Spirit Competition

The Lunabotics Team Spirit Competition is an optional category in the overall competition. A minimum score of 10 out of 15 possible points must be achieved to qualify to win in this category. In the case of a tie, the judges will choose the winning team. The judges' decision is final. The team winning the Team Spirit Award at the Lunabotics Mining Competition will receive a team plaque, individual certificates, and a $500 scholarship.

Lunabotics Team Spirit Competition Scoring Rubric

Elements	3	2	1
Teamwork:			
• Exhibits teamwork in and out of the Lunarena • Exhibits a strong sense of collaboration within the team • Supports other teams with a healthy sense of competition	All three elements are clearly demonstrated	Two elements are clearly demonstrated	One element is clearly demonstrated
Attitude:			
• Exudes a positive attitude • Demonstrates an infectious energy • Motivates and encourages team	All three elements are clearly demonstrated	Two elements are clearly demonstrated	One element is clearly demonstrated
Creativity:			
• Demonstrates creativity • Wears distinctive team shirts or hats • Gives out objects of fun, such as pins, noise makers, etc.	All three elements are clearly demonstrated	Two elements are clearly demonstrated	One element is clearly demonstrated
Engage:			
• Engages audience in team spirit activities • Engages other teams in team spirit activities • Makes acquaintances with members of other teams	All three elements are clearly demonstrated	Two elements are clearly demonstrated	One element is clearly demonstrated

Originality:

• Demonstrates originality in team activities • Displays originality in the team name • Displays originality in the team logo	All three elements are clearly demonstrated	Two elements are clearly demonstrated	One element is clearly demonstrated

Categories for Bonus Points

Collaboration between a majority school with a designated United States Minority Serving Institution
The collaboration between a majority school and a designated U.S. minority serving institution (MSI) must be identified by March 7, 2011 to receive 10 bonus points. MSI student team members must be indicated on the team roster. A list of U.S. minority serving institutions may be found at: http://www2.ed.gov/about/offices/list/ocr/edlite-minorityinst.html. Transcripts must be electronically submitted with the team roster by March 7, 2011.

Multidisciplinary Engineering Teams
Each different science, technology, engineering or mathematics (STEM) discipline represented will count for one bonus point up to a maximum of 10. Disciplines will be indicated on the team roster by March 7, 2011. No bonus points will be given in this category if a team has only one discipline represented. If a member of your team is in a STEM discipline that is not on this list, you may e-mail Susan.G.Sawyer@nasa.gov to request approval of that discipline for the competition.

Aeronautical Engineering
Aerospace Engineering
Astrobiology
Astronautical Engineering
Astronomy
Astrophysics
Atmospheric Sciences
Bacteriology
Biochemistry
Biology
Biophysics
Chemical Engineering
Chemistry
Civil Engineering
Computer Engineering
Computer Science
Electrical Engineering
Engineering Management
Environmental Engineering
Geography
Geosciences
Health Engineering
Industrial/Manufacturing Engineering
Information Technology
Materials/Metallurgical Engineering
Mathematics
Mechanical Engineering
Microbiology
Natural Resource Management
Nuclear Engineering
Oceanography
Optics
Physics
Software Engineering
Systems Engineering

Lunabotics Checklist

Required Competition Elements
If required elements are not received by the due dates, then you are not eligible to compete in any part of the competition (NO EXCEPTIONS).

Registration	February 28, 2011
Systems Engineering Paper	April 18, 2011
Outreach report	April 18, 2011

Optional Competition Elements
Late presentations will not be accepted as part of the presentation competition, but the team is eligible to compete in all other parts of the competition and can make a presentation on site.

Presentation	April 18, 2011
Team Spirit (on-site)	May 23-28, 2011

Required Documentation

Registration	February 28, 2011
Team Roster including	March 7, 2011
○ Participant information	
○ Transcripts (unofficial copy is acceptable)	
○ Media Release Form	
Team Picture	May 3, 2011
Team Biography (250-500 words)	May 3, 2011
Head Count Form	May 3, 2011

Appendix B: System Requirements Review

System and Subsystem Requirements

The following are the system and subsystem requirements for the 2010-2011 JBU Lunabotics as of November 10, 2010.

Overall System Requirements

Functional Requirements *(requirements on what functions the system/subsystem/component must perform)*:

1. The system shall excavate regolith
2. The system shall be able to empty regolith into hopper 1m off the ground
3. The system shall be within the dimensions of (1.5m width x .75m length x 2m height)
4. The system shall take less than 10 minutes set up and 5 minutes take down
5. The system shall use less than 5 MbBW
6. The system shall be operable from alternate location
7. The system shall weigh less than 80 kg

Performance Requirements *(requirements on how well a system/subsystem/component must perform its function)*:

1. The system shall excavate 100 kg of regolith in 15 minutes

Interface Requirements *(requirements on how interacting systems/subsystems/components coordinate activities or mate)*:

1. The system shall be operable with NASA's network
2. The system shall use less than 5 MbBW

Verification Requirements *(requirements that refer to a test, demonstration, analysis or inspection of the performance or operation of an element, most likely to be performed in Phase D)* :

1. The system shall be functional within test lunarena.
2. The system shall be functional within test network.

Other Requirements *(such as reliability, regulatory, safety, physical, technical, environmental considerations)*:

1. The system shall have a minimum of 2 cameras
2. The system shall have a battery voltage monitoring
3. The system shall have a battery power remaining monitoring
4. The system shall have a drive motor current monitoring
5. The system shall have a excavation motor current monitoring
6. The system shall have a regolith collection monitoring
7. The system shall have a bandwidth measurement

Subsystem Requirements:

Electrical Subsystems

-Power System

Functional:

- On board batteries provide effective power to power all on board components on lunabot for 15 minutes.
- Connections must be made correctly throughout the electrical system to ensure proper operation.

Performance:

- Each component must be powered with an efficiency of at least 80%.
- Feedback and noise must be eliminated to provide a reliable electrical system.
- *In order to help manage high current peaks during operation large capacitors will need to be implemented to help with high current pull.*

Interface:

- *Diodes must be implemented to ensure protection to the communications and control systems.*
- Must be as light as possible

-Control System

Functional:

- *The Lunabot shall receive commands from the command center through NASA's network*
- Control two Drive Motors, one excavation motor, and two linear actuators.
- Control system shall use sensors to capture information about the Lunabot and the competition environment.
- *Relay the sensor data back to the command center through NASA's network.*

Performance:

- Must have a lag time of less than .1 seconds

Interface:

- The components of the control system will need to be housed in enclosures that are mounted on the frame.
- The communications system needs to send instructions to the control system using the TCP/IP protocol.
- The other required voltages will depend on the specific devices used
- Control system on board the Lunabot must be as light as possible

.

-Communication System

Functional:

- Time delay under 0.1 seconds as measured by pinging from the laptop to the microcontroller.
- Transmitting under 5 Mb/s of data.
- Must be able to control up to 3 variable speed and 4 level outputs.

Performance:

Interface:

- Communications system on board the Lunabot must be as light as possible
- Send instruction to the control system using the TCP/IP protocol

Verification:

- Transmitting average under 5 Mb/s of data. This may be able to be measured by free software available online.

Mechanical Subsystems:

Must weigh less than the total 80 kg minus the weight of the electrical components

- Movement System

Functional:

- Must be able to maneuver through the obstacle zone
- Distance of at least 50 cm between contact with the ground
- Turning radius less than 3.5 m
- Creep of .05m/s
- Must have 30 cm of ground clearance plus sinkage
- Must have variable speeds

Performance:

- Carry a total load of 180 kg

Interface:

Verification:

- Able to traverse Lunarena from one end to other in under 60 seconds without a carrying a load
- Able to perform all tasks at a slope of 1.5° to account for lunar regolith properties

Other:

-Collection System

Functional:

- Moves regolith from ground to collection bin
- Must be able to move up and down from 30 cm above surface to 5cm below surface

Performance:

- Able to withstand contact with ground without breaking
- Able to handle small rocks
- Excavate 100 kg in 6 minutes
- Collection system must be as light as possible

Interface:

- Will fit within the envelope

-Frame System

Functional:

- Carry a load of 180 kg while maneuvering through the Lunarena
- Support and contain all subsystem components
- Be able to straddle craters up to 30 cm in diameter
- *Be able to cross over rocks 30 cm high*
- Able to manufactured by our team
- Very robust
- Shall not fall over during mining, traversing, and ejecting regolith

- Fit in envelope (1.5m x .75m x 2m)

Performance:

Interface:

- No significant deformation when loaded
- Able to withstand vibrations of driving and excavation

Other:

- *Lighter than JBU 2009-2010 team's frame*
- Easily modified

-Storage System

Functional:

- Must hold regolith without spillage

Performance:

- Must hold 100 kg at 1g /cm^3

Interface:

Verification:

Other:

-Ejection System

Functional:

- Must eject regolith into hopper within 1.5 minutes
- Must eject regolith into hopper 1.1m above regolith surface

Performance:

- Must eject at least 90% of the regolith initially collected

Appendix C: Mass Budget

Table C: Mass Budget

Mass Budget			
Item	Qty	Weight (Kg)	Total (Kg)
Communications	1	2	2
Control Systems	1	2	2
Power Systems	1	5.2	5.2
Frame			
Tubular Frame & Bin Pivot Pin Mounts	1	9.5	9.5
Side Cross Braces (Aluminum Strap)	4	0.163	0.652
Front Cross Braces (Aluminum Strap)	2	0.15	0.3
Subsystem Total		10.452	
Mobility			
Drive Motors w/sprockets	2	5.6	11.2
Wheel Sprockets	4	0.371	1.484
Motor Mounts	2	0.32	0.64
Wheels	4	1.36	5.44
Axles	4	0.5	2
Bearings	8	0.098	0.784
Bolts	16	0.0231	0.3696
Middle Bearing Mounts	2	0.212	0.424
Outer Bearing Mounts	4	0.16	0.64
Drive Chain	4	0.217	0.868
Subsystem Total		23.8496	
Collection			
Collection Chain	2	1.24	2.48
Collection Motor	1	1.36	1.36
Bottom Sprockets	2	0.42	0.84
Drive Sprockets	3	0.491	1.473
Bearings	4	0.098	0.392
Bottom Idler shaft	1	0.458	0.458
Upper Power shaft	1	0.454	0.454
Bottom Bearing Mounts	2	0.228	0.456
Bolts	8	0.0231	0.1848
Tubular Frame	1	6.4623	6.4623
Paddles	20	0.137	2.74
Linear Actuator	1	1.27	1.27
Subsystem Total		18.5701	
Storage/Ejection			
Linear Actuator	1	3.2	3.2
Bin	1	9.31	9.31
Bearings	3	0.098	0.294
Bolts	6	0.023	0.138
Pivot Pin	1	0.985	0.985
Subsystem Total		13.927	
Total Lunabot Mass			**75.9987**

Appendix D: Power Budget

Table D: Power Budget

Power Budget						
Item	**Voltage [VDC]**	**Current [A]**	**Power [W]**	**Time [hr]**	**Energy [Whr]**	**[Ahr]**
Wireless Bridge	12.00	1.00	12.00	0.500	6.00	0.500
Switch	12.00	1.20	14.40	0.500	7.20	0.600
USB / Ethernet HUB	5.00	1.00	5.00	0.500	2.50	0.500
Camera 1 (motorized)	12.00	1.50	18.00	0.500	9.00	0.750
Camera 2	5.00	0.50	2.50	0.500	1.25	0.250
Camera 3	5.00	0.50	2.50	0.500	1.25	0.250
Micro-Controller	12.00	1.00	12.00	0.500	6.00	0.500
Drive Motor R	24.00	8 to 12	192 to 288	0.500	96 to 144	4.000 to 6.000
Drive Motor L	24.00	8 to 12	192 to 288	0.500	96 to 144	4.000 to 6.000
Excavation Motor	12.00	14.00	96.00	0.500	48.00	7.000
Linear Actuator (Belt Lift)	12.00	2.50	12.00	0.500	6.00	1.250
Linear Actuator (Hopper Lift)	12.00	10.00	120.00	0.017	2.00	0.167
Power Subsystem	**Storage [Ahr]**					
Communications / Control	3.350					
Drive System	8.000 to 12.000					
Excavation System	8.417					

Appendix E: Preliminary Design Review

Preliminary Design Review

The following is a preliminary design for the 2010-2011 JBU Lunabotics Team as of November 10, 2010.

Based on the requirements for our system and subsystems, several options for each subsystem were proposed and trade studies were performed. Below are the trade studies as presented in tables and our preliminary designs for each subsystem.

Power subsystem

Conception of Operations for the power subsystem:
The power system will need to provide adequate power for the communications and control systems during the entire 15 minute competition time. The power system will first provide enough power to traverse through the dump and obstacle course sections of the course. After doing this the power system will need to provide enough power to run the excavation motor for approximately 14 minutes; allowing one minute for total time traversing the course. While excavating the power system will be powering the drive motors enough to creep along the mining area. While excavation occurs loading on the lunabot will continue to increase and power consumed will increase at a steady rate. The power system will run any linear actuator as needed to lift and lower the excavation belt. The power system then will power the lunabot as it traverses the obstacle and dump areas where it will power an ejection system to dump the collected regolith.

Options:

Table 1: Battery Network Options

Battery Network	Pros	Cons
1 Battery Network	-One battery to charge -Least weight -Least Cost	- Inefficiencies when regulating voltage -Reliability -A lot of concentrated current discharge
2 Battery Network	-Less batteries to charge -Potentially less weight -Potentially less cost	-Reliability -Concentrated current discharge on 12v battery
3 Battery Network	-More Reliability -Specialized batteries for specific situations	-Potentially more cost -Potentially more weight

Table 2: Battery Technology Options

Battery Technology	**Pros**	**Cons**
Lead Acid	-Low Cost -Easy to find -Reliability - "Friendly" voltage options -Highest discharge rate (typically)	-Very heavy -Low Energy Density -Large in size
NiMH	-High energy density -Reliability - "Friendly" voltage options	-Expensive -Somewhat heavy
Lithium Ion	-Very high energy density -Very lightweight	-Complexity (less reliability?) - "UN-friendly" voltage options -Very Expensive

Ultimately, we have chosen to go with the 3 battery network system and the Lithium Ion battery. Here is what our decisions were based on:

-3 Battery System
- Reliability for communications and control systems
  - By isolating high power components from low power components
- Ability to choose specific battery features for certain situations (higher current discharge capabilities)

-Lithium Ion
- Lightweight
- Higher energy density by mass

Control Subsystem

Conception of Operations:

First, the control systems function is to receive commands that we send from the command center through NASA's network, second, to control the motors and linear actuators and other devices based on those instructions and third to use various sensors to capture information about the Lunabot and the competition environment. Finally, to relay the data from the sensors back to the command center through NASA's network.

Options:

Controlling Motors

Relays would be cheap, reliable, and easy to use. The disadvantage is that they only control the direction and not the speed of the motor. This would not be an important detriment in driving the linear actuators, but would make operating the drive motors very difficult.

A Speed Controller is a relatively complex device in comparison and would not be as easy to configure. They are significantly more expensive, but they effectively control the speed of any attached motors.

Control System

The Gumstix controller is relatively powerful although it is a more expensive option. The Gumstix platform includes a USB host interface which would allow connecting USB devices to the board. Using the Space Plug-and-Play Avionics protocol, it should be relatively easy to interface sensors with the board.

The Arduino board, although much cheaper than a Gumstix computer, should have adequate resources and power to control the lunabot. Since the board is a widely used open-source platform, there are many resources, code libraries, and documentations that would make interfacing with sensors and components easier. The Arduino would not be able to act as a USB host, however, an Ethernet based USB hub could be installed on the Lunabot to replace that feature.

Preliminary Design choice:

We have decided to go with the Arduino board due to the amount of resources available.

We will use speed controllers for the drive motors and the excavation motors since that will allow us to easily vary the speed as needed.
We will use relays for the linear actuators or other motors that we use to operate the hopper and/or raise and lower stuff since we don't really need to have different speeds, and that will save a lot of time and complexity.

Communications subsystem

Concept of Operations:
The communications system will take user control inputs from controlling systems and communicate those through a LAN connection to communication devices onboard the lunabot.

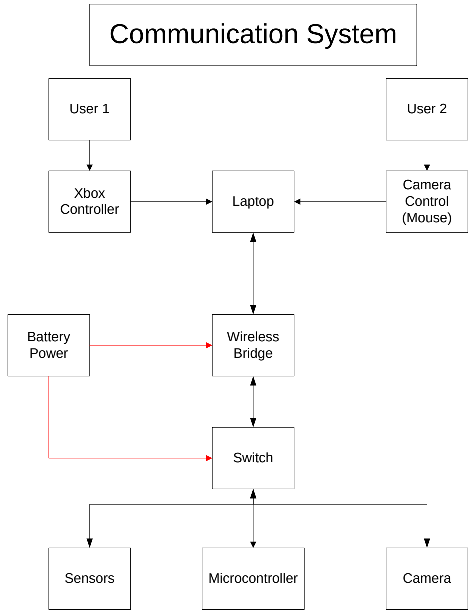


Figure 1: Communications concept of operations flow chart

Options:

Table 3: User Control Options

User Control		
	Pros	Cons
Xbox controller	- Easily handles 2 variable speed outputs - Allows for up to 9 level outputs - Intuitive control interface already understood by users - Programming resources available	- Does not have a third joystick for 3 variable controls
Joystick	- Many variations available with possibility for many buttons	- Only has 1 joystick
Keyboard	- Free, already interfaced with laptop - Most available inputs	- No variable inputs
Autonomous	- No user control necessary	- Very Complex - Needs extra sensors onboard lunabot

Table 4: Communication Options

Communication		
	Pros	Cons
LAN	- NASA has LAN set up at competition - Removes consideration of distance from transmitter to lunabot -Easy to interface with	- Time delay from security encription
Radio Control	- Less time delay - Avoid networking problems	- Transmitter to receiver distance must be considered - Possible interference with signal

Preliminary Design Choice:
Based on the information in table 3 and 4, we decided to go with the Xbox controller for the user control because of the reasons stated in the user control and the Xbox controller had more pros than any other option we looked at. We decided to go with the LAN for our actual communication. There were simply too many unknowns with the radio control mode of communication; NASA has also seemed to recommend using LAN at the competition.

Movement Subsystem

Concept of operations:
Once the competition has begun, the lunabot will initially be placed at a random orientation. The lunabot needs to be able to turn so that it is in the position to traverse across the obstacle zone. The lunabot will then begin to move across the obstacle zone driving over or around any obstacles as it moves. The lunabot must then come to a stop in the excavation zone and the excavation portion of the process will begin. At this point, it may be necessary for the robot to slowly move forward while excavating. Once the excavation is complete, the lunabot will then need to turn around and move back across the obstacle zone back to the starting zone. At this point the lunabot will need to move into position to eject the regolith into the hopper.

Options:

Table 5: Steering Movement Options

	Steering Movement Options	
Options	Advantages	Disadvantages
Skid Steer	Least complex Very strong Few parts Allow for zero turns (pivot on a point) No differential required Easy to make 4-wheel drive	Requires more power Can be harder to drive fast and straight Requires specific width to length wheel base (wider than long)
Wheel Steer	Requires less power Easier to control at high speeds	Much more complex More parts Not as inherently strong Larger turning radius Require differential Not as easy to make 4-wheel drive
Articulate Steering	Less parts than wheel steer Less power required Small turning radius	Requires differentials Less effective at high speeds Harder to make 4-wheel drive More parts than skid steer Moderate complexity

Table 6: Wheels vs. Tracks

	Wheels vs. Tracks	
Options	Advantages	Disadvantages
Tracks	Greatest amount of ground contact area, less likely to get stuck More traction May turn more easily	More expensive More weight More moving parts More likely to break or tracks come off Restricted on sizing options Requires more design work
Wheels	Less expensive Less parts More robust Lighter Less design required Much more easily attainable More easily customized	May have less traction Not as much ground contact area May not turn as tight (greater turning radius)

Preliminary Design options:
Based on tables 5 and 6, we decided to go with skid steer and wheels because we believe that the charts show that they are not only the best options but also the most available and least expensive options.

Collection System

Concept of Operations:

Once the lunabot reaches the excavation zone, the collection subsystem must excavate the regolith, moving it from the lunarena ground to a storage system onboard the lunabot. While traversing the lunarena, the collection system must not compromise the movement of the lunabot.

Options:
For the collection system we considered five options: large scoop, auger (horizontal or vertical), conveyor, collection wheel, and clam shell. We almost immediately eliminated three. The auger would not be able to handle small rocks which is one of our requirements. The collection wheel would be similar to the conveyor but more complex. The clam shell would again have problems with small rocks and would be similar to the scoop concept but more complex. After eliminating the auger, collection wheel and clam shell we went into more depth with the large scoop and the conveyor.

Table 7: Collection Options

	Collection Concepts	
Options	Advantages	Disadvantages
Large Scoop	Simple Faster Easier to construct Most likely less expensive	Subjected to greater loads May have difficulty actually mining Requires faster and more precise response from operator Easier to overload
Conveyor	Should load easily Proven design concept Carries smaller loads Easier to move regolith to a raised storage bin Less parts to manufacture Easier to find inside the envelope Change in center of gravity not influenced as much by the collection system	More complicated More expensive Slower

Based on the information in Table 7, we decided to go with the conveyor concept. While it is more expensive and complicated, these disadvantages are not as great as the disadvantage that the scoop presents. The purpose of the collection system is to excavate the regolith, the large scoop presents too many problems in the actual mining that the conveyor does not.

Frame system

Concept of operations:
All of the on board electrical subsystems and components as well as the mechanical subsystems must be mounted on the frame during the competition. The frame will need to withstand any stresses from the movement of the lunabot, the excavation process, and the load being carried.

Shown below is a figure of our initial design in Figure 2.

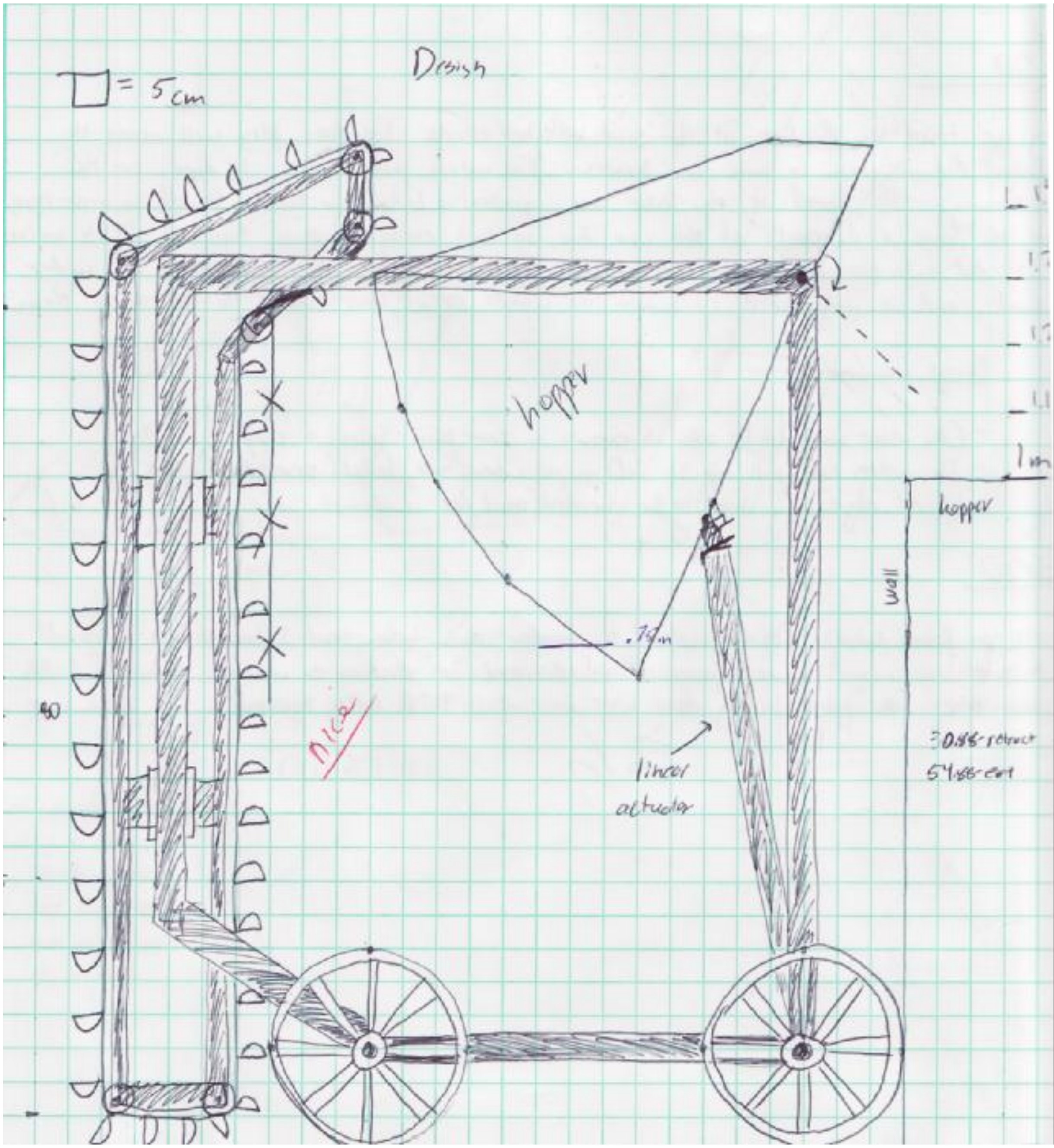


Figure 2: Initial Design drawing

Options:
We considered three different material options for the frame: 80/20, aluminum square tubing, and alloy steel 4130. In analyzing these options we were concerned with not only their strength but their mass. We need something light and strong. We created a ratio to compare all three by dividing their bending moment to their mass.

Table 8: Frame Material Options

Frame Material Options	
Material Options	Ratio
80/20	627.653
Aluminum Square Tubing	690.739
Steel alloy 4130	8491

While the steel alloy clearly had the best strength to weight ratio as shown in table 8, it is the most expensive. At this point, we are considering using possibly all of these options for different portions of the frame.

Ejection and Storage Subsytems:

Concept of Operations:
As regolith is excavated, it will fall into storage bin. After bin is filled to desired mass, lunabot then traverse back across the lunarena to hopper for ejection of regolith. At this point the ejection subsystem would eject the regolith from the lunbot into the hopper located 1m off the lunarena surface.

Options:

Table 9: Ejection Options

	Ejection options	
Options	Advantages	Disadvanatages
Raised vertically (last years design)	Movement in one direction Low center of gravity while traversing lunarena	Power intensive to life load High stress areas while raising large load May create unstable unloading conditions
Raised diagonally	Low center of gravity while traversing lunarena More efficient mining based on bin placement (located directly under conveyor)	Unstable center of gravity while ejecting Movement in more than one direction Long travel distance High stress areas while raising large load
Elevated hopper	No moving parts	Unstable center of gravity
Moderately elevated hopper with pivot point	Allows for low center while traversing lunarena Simple ejection mechanism Fewer moving parts-simpler design	Require a reinforced storage bin
Ejection chain	Allow for low center of gravity for entire competition	Heavier More expensive More complex Collection bin require more slope therefore increasing size

Preliminary Design:

Based on the information show in table 9, we decided to go with the moderately elevated hopper with a pivot point. This is shown in Figure 2. We feel that this option will be the most successful in regards to the stability of our robot and the complexity of the design.

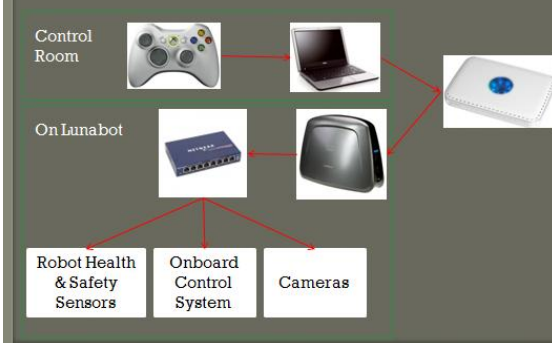
Appendix F: Critical Design Review

Electrical Systems Critical Design Review

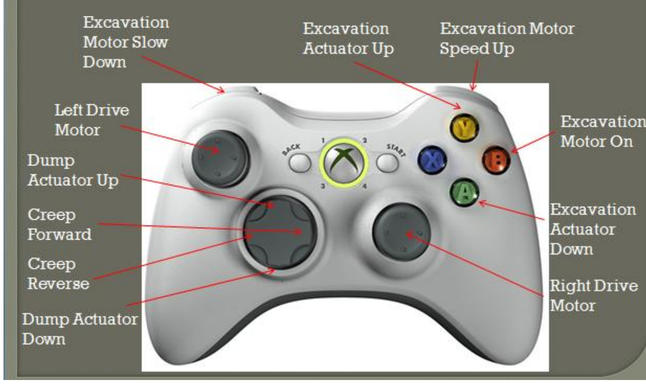
Final Design Review Lunabotics Electrical

Michael Anthes
Marshall Nicholson
David Penner
Susanna Whittaker

Design



User Control



Programming

- Using C# in XNA Game Studio
  - Already set up to program using the Xbox controller
- Packet Sending?
  - Port's and IP addressing

Communications

- Test Bandwidth with free software
  - Under 5 Mb/s
- Freshmen project
- What was usage last year?

Control System Functions

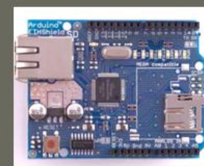
- Receive commands from the command center through the network.
- Control the motors and linear actuators.
- Use sensors to capture information about the Lunabot and the competition environment.
- Relay the sensor data back to the command center through the network.

Arduino Mega 2560
Microcontroller Board

- Uses an Atmel ATmega2560 µC
- 16 analog input pins
- 54 Digital I/O Pins
- 4 Serial ports
- 7-12V Power requirement
- Most functions are well documented

Arduino Ethernet Shield

- Mounts directly on top of an Arduino
- Handles TCP/IP and UDP with a standard Ethernet connector – RJ45.
- Includes an Ethernet library for the Arduino



Sabertooth dual 25A motor driver

- Can supply 25A continuous to each of two DC motors
- 6-24 V input range
- Can be controlled through Analog, R/C, or serial signals
  - Using serial
- Using two identical speed controller to control all three motors allows for more redundancy and less complexity in the design.

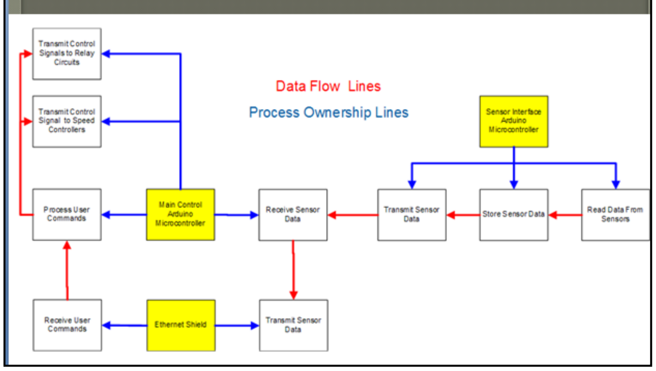
Sensors

- Voltage sensors to monitor the voltage supplied by the batteries
  - Using two resistors in series from voltage supply to ground, the voltage can be divided down to the 0-5V range that the ADC on the Arduino can measure.
- Current sensors to monitor the power being used by the motors
  - Current sensor ICs output an analog voltage that can be read by an ADC.
  - Sensors rated up to 200A are available.

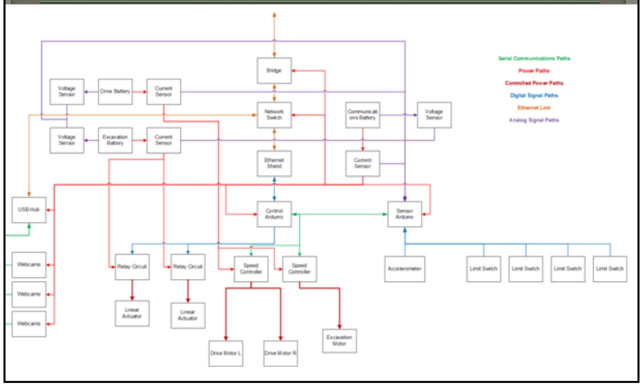
Video - Webcam

- Since processing the data from a webcam would overwhelm the capabilities of most microcontrollers, the video feed would need to bypass the controller.
- Ethernet connected webcams can be purchased but they are expensive
- The Linkskey Network USB hub ($43) functions as a USB hub that can connect to an Ethernet network.
  - Standard USB webcams ($20-30 ea) can be connected to it.

Programming Flow Chart



Subsystem Flowchart



Goals / Constraints

- Power System needs to power the Lunabot effectively, efficiently, and reliably for 30 minutes.
- Power System have a mass < 8kg.
- Keep costs below $1,000.

Testing Last Years Lunabot / Improvements

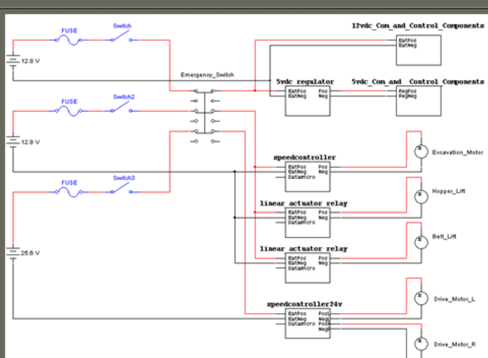
- Tested power demand of the different components:
  - Both wheelchair motors (for mobility)
    - Sand volleyball courts
  - The excavation motor (for mining)
    - New motor needed
  - The linear actuators (for bucket/belt lifting)
    - Charts
  - Communications / Control components
    - Added components
- Improvements
  - Lithium Ion battery network
  - Much higher current rate capabilities on batteries
  - Larger excavation motor
  - Analog circuitry simplified but effective

Power Budget

Item	Voltage [VDC]	Current [A]	Power [W]	Time [hr]	Energy [Whr]	[Ahr]
Wireless Bridge	12.00	1.00	12.00	0.500	6.00	0.500
Switch	12.00	1.20	14.40	0.500	7.20	0.600
USB / Ethernet HUB	5.00	1.00	5.00	0.500	2.50	0.500
Camera 1 (motorized)	12.00	1.50	18.00	0.500	9.00	0.750
Camera 2	5.00	0.50	2.50	0.500	1.25	0.250
Camera 3	5.00	0.50	2.50	0.500	1.25	0.250
Micro-Controller	12.00	1.00	12.00	0.500	6.00	0.500
Drive Motor R	24.00	8 to 12	192 to 288	0.500	96 to 144	4.000 to 6.000
Drive Motor L	24.00	8 to 12	192 to 288	0.500	96 to 144	4.000 to 6.000
Excavation Motor	12.00	14.00	96.00	0.500	48.00	7.000
Linear Actuator (Belt Lift)	12.00	2.50	12.00	0.500	6.00	1.250
Linear Actuator (Hopper Lift)	12.00	10.00	120.00	0.017	2.00	0.167

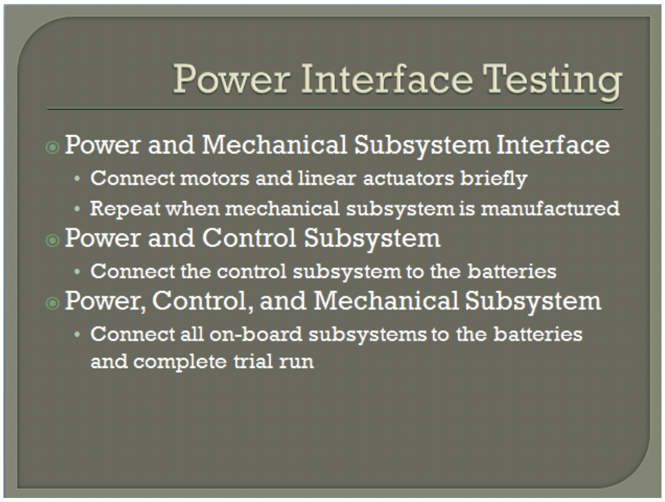
Power Subsystem	Required Storage [Ahr]
Communications / Control	3.350
Drive System	8.000 to 12.000
Excavation System	8.417

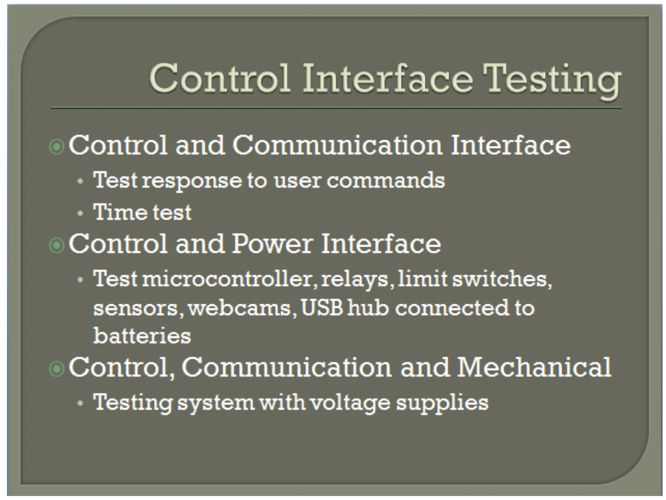
Power Circuitry

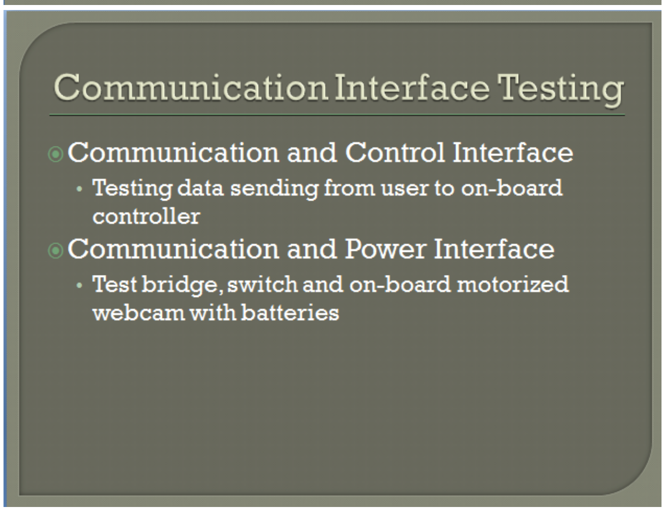


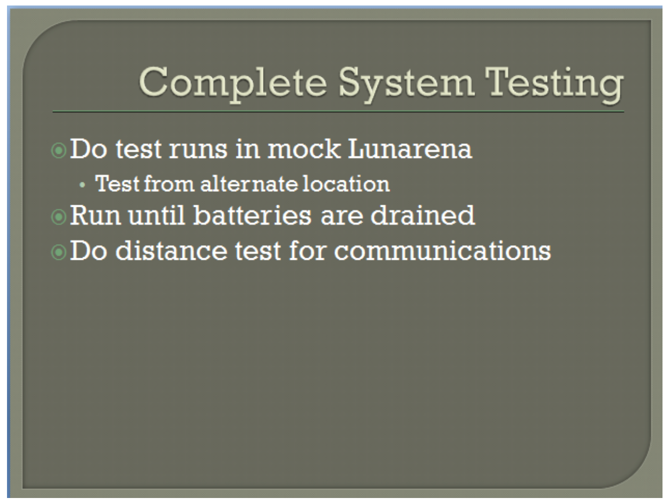
Testing

- Testing 3 batteries for actual capacity in [Ahr]
- Testing if voltage regulation is necessary on 12v components
- Add more Systems to testing process as results continue to be acceptable
- Test power system with onboard communications / control components
- Test electrical system with mechanical system


Power Interface Testing
Power and Mechanical Subsystem Interface
Connect motors and linear actuators briefly
Repeat when mechanical subsystem is manufactured
Power and Control Subsystem
Connect the control subsystem to the batteries
Power, Control, and Mechanical Subsystem
Connect all on-board subsystems to the batteries and complete trial run


Control Interface Testing
Control and Communication Interface
Test response to user commands
Time test
Control and Power Interface
Test microcontroller, relays, limit switches, sensors, webcams, USB hub connected to batteries
Control, Communication and Mechanical
Testing system with voltage supplies


Communication Interface Testing
Communication and Control Interface
Testing data sending from user to on-board controller
Communication and Power Interface
Test bridge, switch and on-board motorized webcam with batteries


Complete System Testing
Do test runs in mock Lunarena
Test from alternate location
Run until batteries are drained
Do distance test for communications

Mechanical Subsystems Critical Design Review

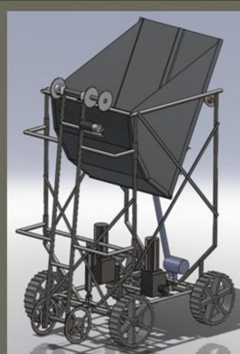
Mechanical Systems

Billy Strnad
Susanna Whittaker

Overview

- Design Drawing
- Time Budget
- Mass Budget
- Frame System
- Mobility System
- Collection System
- Storage/Ejection System

Design



Time Budget

Time (Minutes)	% of Total Time	Description
1	6.67	Establish communications and initialize systems
2	13.33	Move into position to cross obstacle course
1	6.67	Move into position and prepare for mining
6	40	Mining
2	13.33	Retract collection system and cross obstacle course
2	13.33	Position Lunabot at the hopper
1	6.67	Deposit regolith
15	100	Total

Mass Budget

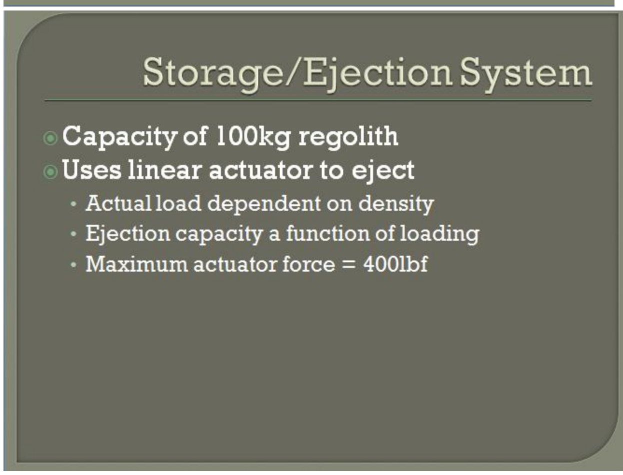
- See Handout

Frame System

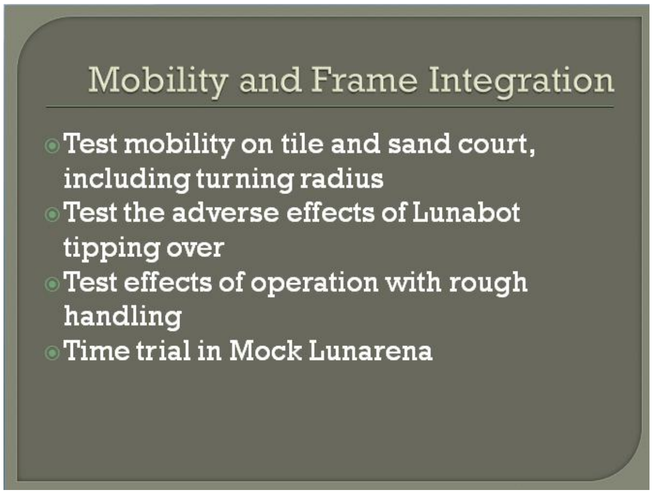
- .875"OD, 1/16" wall 4130 Tubing

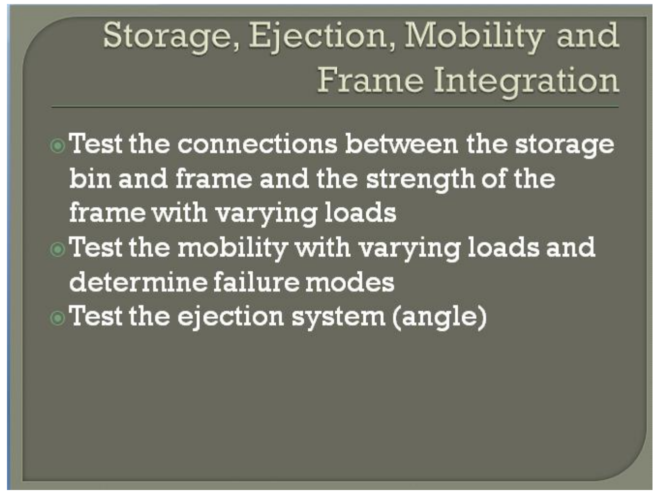

Mobility System
Wheelchair motors
Plastic wheels
Skid steer
Improved wheel aspect ratio
Slower gear ratio

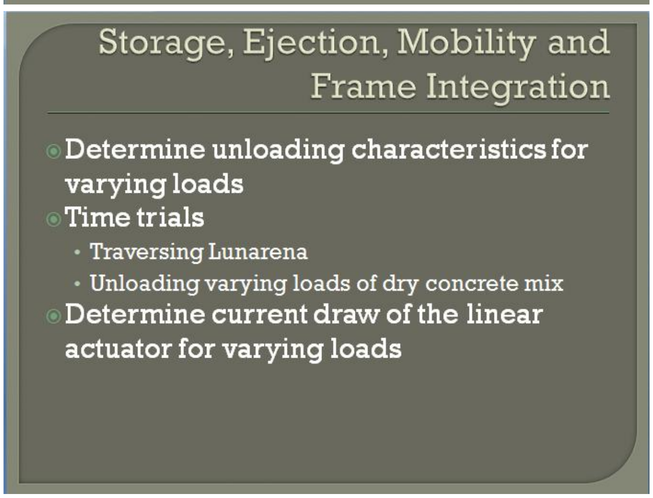

Collection System
Utilizes paddles on a collection chain
Paddles:
D=1.325"
Length=20"
Number=20
For .1m^3 regolith:
5.5 swaths @ 3 meters/each (depth of 1cm)
Using dig efficiency of 25%
Gearmotor w/chain drive
Regolith is "thrown" into collection bin

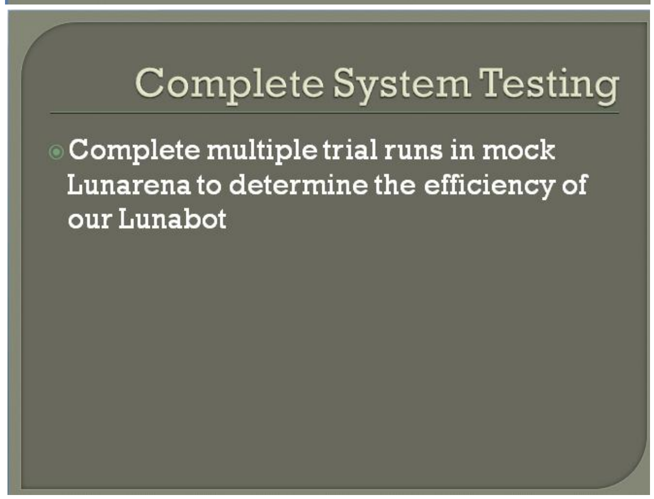

Storage/Ejection System
Capacity of 100kg regolith
Uses linear actuator to eject
Actual load dependent on density
Ejection capacity a function of loading
Maximum actuator force = 400lbf


Testing
Susanna Whittaker
Power and Mechanical Subsystem Interface
Connect motors and linear actuators briefly
Repeat when mechanical subsystem is manufactured
Control, Communication and Mechanical
Testing system with voltage supplies


Mobility and Frame Integration
Test mobility on tile and sand court, including turning radius
Test the adverse effects of Lunabot tipping over
Test effects of operation with rough handling
Time trial in Mock Lunarena


Storage, Ejection, Mobility and Frame Integration
Test the connections between the storage bin and frame and the strength of the frame with varying loads
Test the mobility with varying loads and determine failure modes
Test the ejection system (angle)


Storage, Ejection, Mobility and Frame Integration
Determine unloading characteristics for varying loads
Time trials
Traversing Lunarena
Unloading varying loads of dry concrete mix
Determine current draw of the linear actuator for varying loads


Complete System Testing
Complete multiple trial runs in mock Lunarena to determine the efficiency of our Lunabot

Appendix G: Interfaces

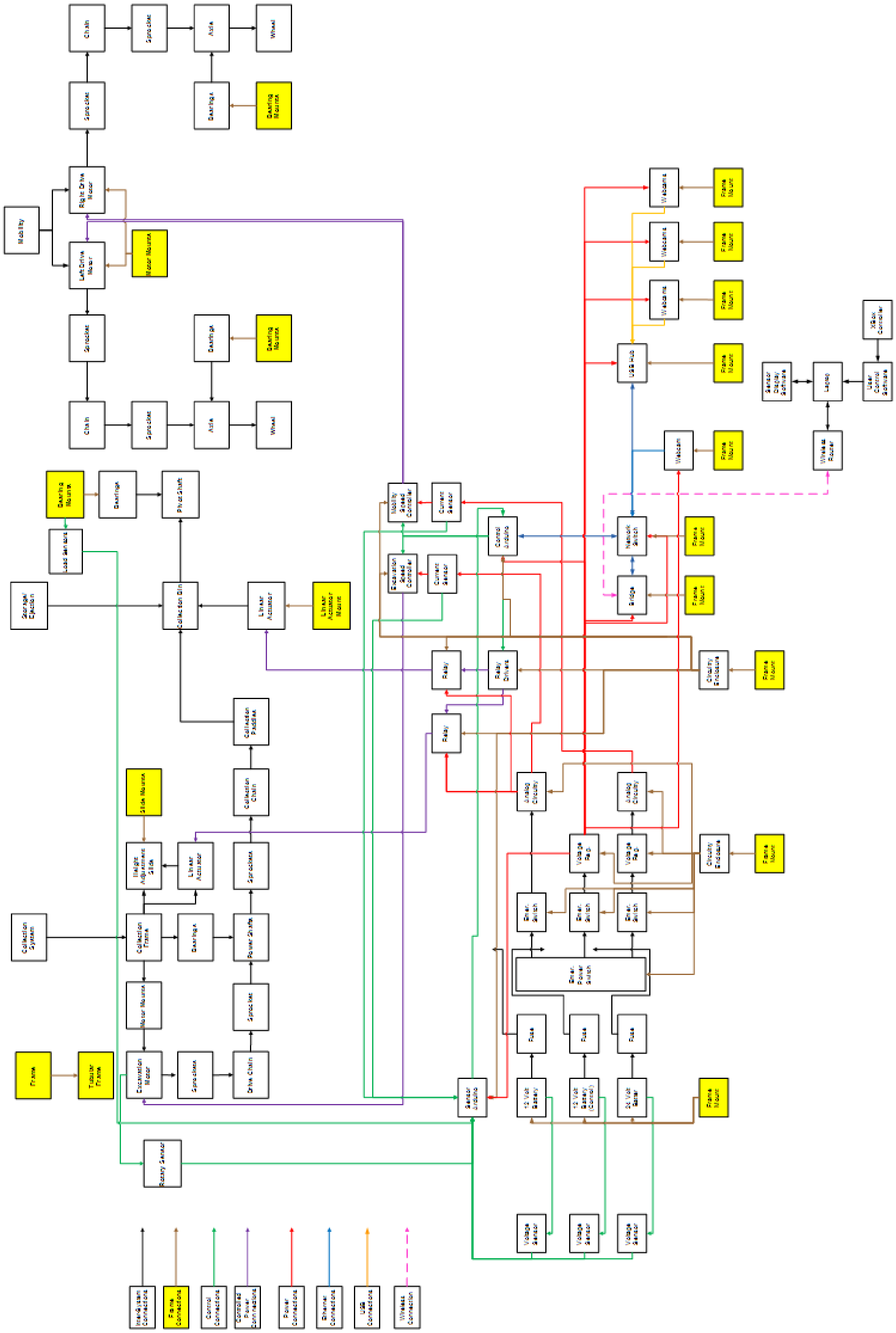


Figure G: Interfaces

Appendix H: Mobility Trade-Off Assessment

Table H: Mobility Trade-Off Assessment

Mobility Options		
	Advantages	**Disadvantages**
Wheels	Less expensive	May have less traction
	Less Parts	Not as much ground contact
	More Robust	Greater turning radius
	Less weight	
	More accessible	
	Easier to customize	
Tracks	Greatest amount of ground clearance	More expensive
	More traction	More weight
	Smaller turning radius	More complex (more moving parts)
		More likely to break or tracks come off
		Restricted on sizing options

Appendix I: Complete Risk Analysis

Technical Risk Analysis

The following are potential threats or uncertainties contained in this project; the following have been identified and organized by number to put in the qualitative risk assessment chart (Figure 33).

System

00.1 Team member fails to operate system correctly.

00.2 Lunabot is damaged in transit to Florida.

Power

10.1 Connections within power subsystem come lose.

10.2 Battery drainage prevents operation.

10.3 Current spikes destroy fuse.

10.4 Improper connection with the power system.

10.5 Short circuit prevents operation.

10.6 Improperly charged, over charged battery prevents operation.

Mobility

20.1 Wheels lose traction.

20.2 System not able to maneuver around obstacles.

20.3 Lunabot cannot turn.

20.4 Motors not able to move Lunabot.

20.5 Chains come off sprockets for wheels preventing operation.

20.6 Motors electrically fail preventing operation.

20.7 Wheel breaks preventing mobility.

20.8 Sheared key preventing mobility.

20.9 Axle breaks preventing mobility.

Collection

21.1 Motor fails electrically preventing collection.

21.2 Drive chain breaks or jumps sprocket preventing collection.

21.3 Excavation chain jumps sprocket preventing collection.

21.4 Excavation chain breaks preventing collection.

21.5 Excavation chain, individual chains become unsynchronized preventing collection.

21.6 Break a paddle slowing collection.

21.7 Regolith too condensed to collect preventing collection.

21.8 Excavation frame fails preventing collection.

21.9 Positioning mechanism fails (linear actuator) preventing or slowing collection.

21.10 Natural vibrations shake regolith out of scoops en route to bin preventing or slowing collection.

Storage

22.1 Not able to hold enough regolith because of uneven loading slowing excavation.

22.2 Not able to retain regolith slowing or preventing excavation.

22.3 Collection bin collapses preventing excavation or ejection.

Ejection

23.1 Linear actuator unable to move load preventing ejection.

23.2 While raising bin, frame collapses preventing ejection.

23.3 Collection bin becomes unattached from frame preventing ejection.

23.4 Center of gravity becomes too high and Lunabot capsizes preventing ejection.

23.5 Regolith fails to exit collection preventing ejection.

Frame

24.1 Frame fails due to bending preventing operation.

24.2 Frame fails in shear preventing operation.

24.3 Welds break preventing operation.

Communication

60.1 Wrong IP addressing preventing communication.

60.2 Router failure preventing communication.

60.3 X – box preventing communication.

60.4 Incorrect programming control from X – box preventing communication.

60.5 Incorrect programming communication to microcontroller preventing communication.

60.6 Camera improper connections preventing view.

60.7 Attenuation in the air preventing communication.

60.8 Network failure preventing communication.

60.9 Time delay too great for accurately controlling Lunabot preventing effective operation.

60.10 Camera blocked by dust preventing view.

Control

70.1 Electro static discharge destroys microcontroller preventing control.

70.2 Overheating microcontroller from dust preventing control.

70.3 Overheating microcontroller from too much current preventing control.

70.4 Short circuit due to vibration preventing control.

70.5 Short circuit due to incorrect installation preventing control.

70.6 Programming loopholes preventing control.

70.7 Sensor malfunction due to too much current preventing information to control room.

70.8 Sensor malfunction due to physical damage preventing information to control room.

70.9 Optical sensor blocked by dust preventing information to control room.

Probability

Consequences	Low	Medium	High
High	10.2, 10.4, 10.5, 10.6, 20.4, 20.5, 20.6, 20.7, 20.8, 20.9, 21.1, 21.2, 21.4, 21.8, 22.1, 22.2, 22.3, 23.3, 24.2, 24.3, 60.1, 60,2, 60.3, 60.4, 60.5, 60.6, 60.7, 60.8, 70.3, 70.5, 70.6	00.1, 10.1, 20.1, 20.2, 20.3, 21.3, 21.5, 21.7, 21.9, 21.10, 23.1, 23.2, 23.4, 23.5, 24.1, 70.1, 70.2, 70.4	10.3
Medium	60.10, 70.7, 70.8	00.2, 60.9	
Low			21.6, 70.9

Figure I. Qualitative Risk Assessment Chart

The qualitative risk assessment chart helps sort the risks into three categories, low, moderate and high risk. The low risks are any risks in the boxes that are low probability – low consequences, low probability – medium consequences, and medium probability – low consequences. The moderate risks are located in low probability – high consequences, medium probability – medium consequences, and high probability – low consequences. The high risks are located in the gray are of the chart found in Figure 33. These are the medium probability – low consequences, high probability – high consequences, and high probability – medium consequences categories.

Risk Mitigation Strategies

High Risk - Risk Mitigation

1. Current spikes destroy fuses (*10.3*) – To prevent overloading of electrical components and possible failure, fuses will be installed to open the circuit if an excessive current is drawn. However, the team must install fuses that can handle appropriate current spikes during the competition. Doing test runs in a simulated Lunarena will ensure the fuses can handle the spikes.

2. Failure to operate it correctly (*00.1*) –The software will be designed to eliminate as much human error as possible. Additionally, the team will spend a great amount of time practicing driving the Lunabot around in a simulated Lunarena. Every team member will be able to drive the Lunabot, although for the competition the most capable member will drive.

3. Connections coming lose in power subsystem (*10.1*) – To prevent the connections from coming loose, the connections will be securely attached and strain reliefs will be installed. During testing, these connections will be monitored to make sure they stay intact.

4. Wheels lose traction (*20.1*) – While the team hopes their design will not prove to be a problem in the packed down regolith, one way to mitigate this risk will be careful driving.

5. Not able to maneuver around obstacles (*20.2*) – The team has designed a robot that will be able to go over the craters, but possibly not all of the rocks. The team is hoping that their random placing will still make it possible to maneuver around all the obstacles.

6. Cannot turn (*20.3*) – To prevent this from happening, the team will rely on their design and careful driving of the Lunabot.

7. Excavation chain jumps sprocket (*21.3*) – The excavation system will be designed such that the chain does not come in contact with the ground and always maintains a certain distance from the ground.

8. Excavation chain, individual chains become unsynchronized (*21.5*) – The chain will be kept tight and care will be taken to make sure the chains are the same length and have the same tension.

9. Regolith too condensed to collect (*21.7*) – If the regolith is too condensed to collect, the only option is to find a place within the Lunarena that the regolith is less condense. The team will also make the edges of their scoops slightly beveled too help get the top layer.

10. Positioning mechanism fails (linear actuator) (*21.9*) – If this fails there is nothing that can be done during the competition.

11. Natural vibrations shake regolith out of scoops en route to bin (*21.10*) – If this begins to be evident of a problem, the team will have to gather more regolith that their goal, or try and make more than one run.

12. Linear actuator unable to move load (*23.1*) – The only way to prevent this from being a problem, will be doing practice runs to find how much regolith the linear actuator can move.

13. While raising bin, frame collapses (*23.2*) – If this happens during the competition, there is nothing that can be done.

14. Center of gravity become too high and Lunabot capsizes (*23.4*) – The team will prevent this by doing trials runs in Florida before the competition.

15. Regolith fails to exit collection (*23.5*) – One way the team can help prevent this problem is to slightly move the Lunabot causing the regolith to be shaken from the collection bin.

16. Frame fails due to bending (*24.1*) – If this happens during the competition the team cannot do anything to fix the problem. Practicing will help to know how much the Lunabot can hold.

17. Electro static discharge destroy microcontroller (70.1) – To mitigate this risk the microcontroller will be placed inside an enclosure, grounded and teammates will wear anti static wrist straps while handling the microcontroller.

18. Overheating microcontroller from dust (*70.2*) – The team will prevent this by designing an enclosure for the microcontroller.

19. Short circuit due to vibration (*70.4*) – The team will mitigate this risk by securing every connection and make sure the wires cannot vibrate against the frame.

Moderate Risk

20. Battery drainage (*10.2*) – To mitigate this risk, the team will charge the battery before the competition.

21. Improper connection (*10.4*) – To mitigate this risk, the team will have diagrams of what the design should look like as well as have tested that design and will double check it

22. Short circuit (*10.5*) – To mitigate this risk, the team connects everything correctly and securely.

23. Improperly charged, over charged (*10.6*) – This risk will come down to following the manufacturer's directions.

24. Motors not able to move Lunabot (*20.4*) – To mitigate this risk, the team will design correctly, test before going to Florida and prior to the competition while in Florida. The team will also make sure the Lunabot does not get overloaded with regolith.

25. Chains come off sprockets for wheels (*20.5*) – To mitigate this risk the team will make sure the chains are tight.

26. Motors electrically fail for the mobility system (*20.6*) – To mitigate this risk, the team will design with motors big enough for the load they need to carry.

27. Wheel breaks (*20.7*) – To mitigate this risk, the team will drive the Lunabot carefully.

28. Sheared key for the wheels (*20.8*) – To mitigate this, the team will design with a big enough key width.

29. Axle breaks (*20.9*) – To mitigate this risk, the team will drive the Lunabot carefully and try to not run into the obstacles.

30. Motor fails electrically for the collection system (*21.1*) – To mitigate this risk, the team will design with a motor large enough to carry the load the paddles are collecting.

31. Drive chain breaks or jumps sprocket (*21.2*) – The excavation system will be designed such that the chain does not come in contact with the ground and always maintains a certain distance from the ground.

32. Excavation chain breaks (*21.4*) – The excavation system will be designed with a chain robust enough to handle the movement and load.

33. Excavation frame fails (*21.8*) – The excavation system will be designed with a frame robust enough to handle the movement and load.

34. Not able to hold enough regolith because of uneven loading (*22.1*) – To mitigate this problem the team will have a camera to view the storage and if it suffers from uneven loading, the operator can cause vibrations causing the regolith to move within the storage bin.

35. Not able to retain regolith (*22.2*) – To mitigate this problem, the team will do trial runs in Florida in the days leading up to the competition. If this is a problem, the team will design a solution before the actual competition.

36. Collection bin collapses (*22.3*) – The team will do testing with a maximum load during the design process

37. Collection bin become unattached from frame (*23.3*) – To mitigate this problem the team will make sure the collection bin is attached well by bearings as well as the bearing mounts.

38. Frame fails in shear (*24.2*) – To prevent this from happening, the team will design the frame to ensure that not part of the frame will be put under more than its strength. There will also be extensive testing prior to the competition.

39. Welds break (*24.3*) – To prevent the welds from failing while welding, care will be taken to ensure the maximum amount of strength is retained by the material. There will also be extensive testing prior to the competition.

40. Wrong IP addressing (*60.1*) – To prevent this from happening, the team will test the robot before the fifteen minutes starts for the competition.

41. Router failure (*60.2*) – There is nothing that the team can do to mitigate this risk. It's likely hood is very small.

42. X – box controller fails (*60.3*) – Aside from handling the X – box controller carefully, there is nothing the team can do to prevent the X – box controller from failing.

43. Incorrect programming control from X – box (*60.4*) – The team will prevent this by doing a large amount of testing before going to Florida and during the testing time in Florida.

44. Incorrect programming communication to microcontroller (*60.5*) – The team will prevent this by doing a large amount of testing before going to Florida and during the testing time in Florida.

45. Attenuation in the air (*60.7*) – There is nothing the team can do to mitigate this risk.

46. Network failure (*60.8*) – There is nothing the team can do to mitigate this risk.

47. Overheating microcontroller from too much current (*70.3*) – The team would mitigate this risk by doing a lot of testing and making modifications before going to Florida.

48. Short circuit due to incorrect installation (*70.5*) – The team will have schematics of the correct way of installation; the teammates will also double check each other's work after installation.

49. Programming loopholes (*70.6*) – The team will mitigate this risk by doing testing under all possible circumstances to find any loopholes and correct them before the competition.

50. Lunabot is damaged in transit to Florida (*00.2*) – There are two ways the team will plan ahead for this type of risk. The first will be to drive the Lunabot to Florida themselves, therefore not allowing it to be tossed around. Secondly, the team will be bringing as many back up parts as possible, therefore almost anything that break can be fixed before the competition.

51. Time delay too great for accurately controlling Lunabot (*60.9*) –The team will prevent this by doing a great deal of testing and either redesigning the time delay or learning to operate the Lunabot accurately with the given time delay.

52. Break a paddle (*21.6*) – To prevent this problem the team will not really change anything because there will be multiple paddles. If one paddle breaks, it will not be a problem as long as the others don't break as well.

53. Optical sensor blocked by dust (*70.9*) – The team cannot really do anything to mitigate this risk but it has low consequences because there are other sensors, like the cameras to receive data from the Lunabot.

Low Risk

54. Camera blocked by dust (*60.10*) – The team cannot do anything to mitigate this risk, but the likelihood that the cameras will both be blocked by so much dust the Lunabot is inoperable is thought to be highly unlikely.

55. Sensor malfunction due to too much current (*70.7*) – To mitigate this, the team will do a great deal of testing before the competition but it if malfunctions during the contest the team will still be able to operate the Lunabot.

56. Sensor malfunction due to physical damage (*70.8*) – To mitigate this risk the team will handle the Lunabot carefully as well as operate it carefully so as not to cause any physical damage to the sensors. The sensors will also be securely attached to the Lunabot therefore avoiding shifting or harsh contact with the Lunabot itself.

Appendix J: Excavation Trade-Off Assessment

Table J: Excavation Trade-Off Assessment

Excavation Options		
	Advantages	**Disadvantages**
Large Scoop	Simple	Subjected to greater loads, requires more power and stronger material
	Faster	May have difficulty mining
	Easier to fabricate	Requires faster and more precise response from operator
	Less expensive	Easier to overload
Conveyor	Easy to load	More complex
	Proven design	More expensive
	Loads are smaller, therefore less power required	Easier to fit inside envelope
	Less parts to manufacture	Does not affect center of gravity change
		Slower

Appendix K: Storage/Ejection Trade-Off Assessment

Table K: Storage/Ejection Trade-Off Assessment

Ejection options

Options	**Advantages**	**Disadvantages**
Raised vertically (last year's design)	Movement in one direction Low center of gravity while traversing Lunarena	Power intensive to life load High stress areas while raising large load May create unstable unloading conditions
Raised diagonally	Low center of gravity while traversing Lunarena More efficient mining based on bin placement (located directly under conveyor)	Unstable center of gravity while ejecting Movement in more than one direction Long travel distance High stress areas while raising large load
Elevated hopper	No moving parts	Unstable center of gravity
Moderately elevated hopper with pivot point	Allows for low center while traversing Lunarena Simple ejection mechanism Fewer moving parts-simpler design	Require a reinforced storage bin
Ejection chain	Allow for low center of gravity for entire competition	Heavier More expensive More complex Collection bin require more slope therefore increasing size

Appendix L: Power Testing

The goal of the power system is to provide adequate power to the components on board the lunabot for a 15 minute period of time. As a team requirement our power system must run for a 30 minute period. The power system needs to be estimated because power consumption is based off a lot of unknown variables such as: wheelbase, gear ratio's, excavation surface, components, etc. The following tests were conducted with last years lunabot in the sand volleyball courts to simulate performance in the lunar regolith. The team thinks that performance in the sand would simulate a worst case scenario because sinkage in the sand is much greater than in the lunar regolith. This assumption was based off information in Appendix B reguarding performance in lunar regolith. Testing was performed in the sand volleyball courts with no external load and was attempted with a 100kg external load. Testing was also performed in the tile without an external load and with a 100kg external load. The numbers shown represent power consumption for (1) 24VDC drive motor. A performance factor was calculated for power performance in the lunar regolith. The actual power calculations and performance factor are calculated from the following tests:

Full speed in sand with no external load. (only the 80kg lunabot)

$V_{snl} := 26.12V$	Voltage while in sand with no load
$I_{snl} := 7.1A$	Current pulled in sand with no load
$P_{snl} := V_{snl} \cdot I_{snl} = 185.452\,W$	Instantaneous power
$t := .5hr$	Time length
$E_{snl} := P_{snl} \cdot t = 3.338 \times 10^{5}\,J$	Energy consumed

Full speed on tile with no external load. (only the 80kg lunabot)

$V_{tnl} := 26.12V$	Voltage while on tile with no load
$I_{tnl} := 5.0A$	Current pulled on tile with no load
$P_{tnl} := V_{tnl} \cdot I_{tnl} = 130.6\,W$	Instantaneous power
$t := .5hr$	Time length
$E_{tnl} := P_{tnl} \cdot t = 2.351 \times 10^{5}\,J$	Energy consumed

Full speed on tile with 100kg external load. (with 80kg of lunabot)

$V_{tl} := 26.12V$	Voltage while on tile with an external 100kg load
$I_{tl} := 7.0A$	Current pulled on tile with an external 100kg load
$P_{tl} := V_{tl} \cdot I_{tl} = 182.84\,W$	Instantaneous power
$t := .5hr$	Time length
$E_{tl} := P_{tl} \cdot t = 3.291 \times 10^{5}\,J$	Energy Consumed

Full speed in sand with 100kg external load. (with 80kg of lunabot)

The lunabot from last years team could not move in the sand with an external 100kg load. A power factor was calculated using the information above by using ratio's. The voltage will remair constant, but current pull will increase due to the regolith. The current results were used to calculate the regolith performance factor. Sinkage in the regolith will also increase the surface area in contact with the lunar regolith to account for this a factor of 1.2 was also included in the consumption estimation.

$F_{salr} := 1.2$ — Power performance factor for increasing surface area with lunar regolith

$F_{lr} := \frac{I_{sn1}}{I_{tn1}} = 1.42$ — Power performance factor for lunar regolith

$V_{s1} := 26.12V$ — Voltage while in sand with an external 100kg load

$I_{s1} := I_{t1} \cdot F_{lr} \cdot F_{salr} = 11.928\,A$ — Current pulled in sand with an external 100kg load

$P_{s1} := V_{s1} \cdot I_{s1} = 311.559\,W$ — Instantaneous Power

$t := .5hr$ — Time Length

$E_{s1} := P_{s1} \cdot t = 5.608 \times 10^{5}\,J$

$E_{s1} := 155.77W \cdot hr$ — Energy consumed

Breaking down the excavation time period was pivotal in determining a more accurate estimate on power consumption. This is because mass is changing as the lunabot is excavating. The total time to be accounted for is 15 minutes. Power consumption is calculated for one motor. The calculations are broken down as follows:

STAGE 1: Establishing communications/initialize system, cross obstical course, prepare for mining (contains no loading other than the mass of the lunabot).

$t_1 := .0666667hr$ — Time in STAGE 1

$E_1 := P_{sn1} \cdot t_1 = 4.451 \times 10^{4}\,J$

$E_1 := 12.36W \cdot hr$ — Energy consumed in STAGE 1

STAGE 2: Mining regolith, lifting belt linear actuator to turn, turning, running excavation motor (includes power increase for continuous loading).

$t_2 := .1hr$ — Time in STAGE 2

$E_2 := \int_0^{t_2} P_{sn1} + V_{s1} \cdot I_{s1} \cdot t\,dt$ $\quad E_2 := 20.103W \cdot hr$ — Energy consumed in STAGE 2

STAGE 3: Cross obstacle cource, line up lunabot to hopper, lift bucket and dump. (contains a total lunabot mass of 180kg).

$t_3 := .0833333 \cdot hr$ Time in STAGE 3

$E_3 := P_{s1} \cdot t_3 = 9.347 \times 10^4 J$

Energy consumed in STAGE 3

$E_3 := 25.96W \cdot hr$

Total Energy usage is calculated by adding E1, E2, and E3. These numbers resemble the energy consumption for one drive motor. The result is then multiplied by 2 to account for the second motor.

$E_{total} := E_1 + E_2 + E_3 = 2.103 \times 10^5 J$

Energy total for 1 drive motor and 15 minute period

$E_{total} := 58.42W \cdot hr$

$E_{total2motors} := E_{total} \cdot 2 = 4.206 \times 10^5 J$

Energy total for 2 drive motors and a 15 minute period

$E_{total2motors} := 116.84W \cdot hr$

$E_{total2motors30mins} := 233.69W \cdot hr$ Energy total for 2 drive motors and a 30 minute period

Turning is another area where a lot of energy will be consumed. The lunabot pulled nearly 40 amps of current total while skid steering (20A to each motor). The voltage will remain the same. Turning is estimated to take approximately 10 seconds to turn 180 degrees from the origninal position. It is estimated that the lunabot will make 20 180 degree turns. The following calculations are based on the use of both drive motors.

$V_{turn} := 26.12 \cdot V$ Voltage during a turn

$I_{turn} := 40A$ Current pulled by a single turn (both motors)

$P_{turn} := V_{turn} \cdot I_{turn} = 1.045 \times 10^3 W$ Power during a turn

$t_{turn} := .055556hr$ Time alloted for all turning (20 turns at 10 seconds each)

$E_{turn} := P_{turn} \cdot t_{turn} = 2.09 \times 10^5 J$

Energy total consumed for turning

$E_{turn} := 58.05W \cdot hr$

$E_{turn30min} := 116.1W \cdot hr$ Energy total consumed for turning for 30 minute period

The total amount of energy consumed by the drive motors for 30 minute period is calculated by adding the E(turn30min) and E(total2motors30mins) components.

$E_{Grandtotal} := E_{turn30min} + E_{total2motors30mins} = 1.259 \times 10^6 J$

Total Energy Consumed

$E_{Grandtotal} := 349.72W \cdot hr$

Calculating the energy consumed by the excavation system was a little more difficult. The excavation system is made up of an excavation motor, belt lift, and a hopper lift. Up until this point the team is still not sure what motor they are going to implement for the excavation system. The team made calculations based on the worst case scenario. This meant that last years excavation motor would not work and they would have to buy another motor that can provide proper torque and rpm requirments for the design. Designing for worst case would allow the team to implement the new motor if they had to without effecting the power system. All calculations were based off the requirements and manufacturer estimates. The current estimates were calculated by the manufacturer based on the teams rpm and torque requirements.

Excavation Motor:

$RPM := 600$ Required RPM rating

$Torque := 15\frac{in}{lb}$ Required Torque

$I_{estimated} := 12A$ Current pulled at required RPM and Torque (esimated by manufacturer)

$V_{exmotor} := 14.4V$ Voltage required by excavation motor

$t_{excavation} := .5hr$ Possible time excavation motor could be on

$P_{exmotor} := I_{estimated} \cdot V_{exmotor} = 172.8\,W$ Power consumed by excavation motor

$E_{exmotor} := P_{exmotor} \cdot t_{excavation} = 3.11 \times 10^{5}\,J$

$E_{exmotor} := 86.38W \cdot hr$ Energy consumed by excavation motor

Calculating the energy for the linear actuators on board the lunabot is another area that needs to be calculated to properly design the power system. Current ratings were found on the manufacturers website. The hopper current rating was figured considering it was full of 100kgs of regolith. The hopper lift is projected to take 2 minutes to lift with 100kgs of regolith.

Belt Lift:

$V_{BL} := 14.4V$ Voltage required by belt lift

$I_{BL} := 2A$ Current required by belt lift

$t_{BL} := .5hr$ Time belt lift could run

$P_{BL} := V_{BL} \cdot I_{BL} = 28.8\,W$ Power consumed by belt lift

$E_{BL} := P_{BL} \cdot t_{BL} = 5.184 \times 10^{4}\,J$

$E_{BL} := 14.4W \cdot hr$ Energy consumed by belt lift

Hopper Lift:

$V_{HL} := 14.4V$ Voltage required by hopper lift

$I_{HL} := 10A$ Current required by hopper lift

$P_{HL} := V_{HL} \cdot I_{HL} = 144\,W$ Power consumed by hopper lift

$t_{HL} := .03333hr$ Time hopper lift could run

$E_{HL} := P_{HL} \cdot t_{HL} = 1.728 \times 10^{4}\,J$

$E_{HL} := 4.8W \cdot hr$ Energy consumed by hopper lift

The total energy consumed by the Excavation System is shown below:

$E_{exctotal} := E_{BL} + E_{HL} + E_{exmotor} = 3.801 \times 10^{5}\,J$ Energy consumed by excavation system

$E_{exctotal} := 105.5833W \cdot hr$

The communications and control systems are the last that need power on board the lunabot. This inculdes webcams, sensors, networking equipment, microcontrollers, etc. The energy consumption calculations are based off of required input current and voltage numbers.

Camera:

$V_{cam} := 12V$

$I_{cam} := 1.5A$

$t_{cam} := .5hr$

$P_{cam} := V_{cam} \cdot I_{cam} = 18\,W$

$E_{cam} := P_{cam} \cdot t_{cam} = 3.24 \times 10^{4}\,J$

$E_{2cam} := E_{cam} \cdot 2 = 6.48 \times 10^{4}\,J$

$E_{2cam} := 18W \cdot hr$

Switch:

$V_{switch} := 12V$

$I_{switch} := .7A$

$t_{switch} := .5hr$

$P_{switch} := V_{switch} \cdot I_{switch} = 8.4\,W$

$E_{switch} := P_{switch} \cdot t_{switch} = 1.512 \times 10^{4}\,J$ $\quad E_{switch} := 4.2W \cdot hr$

Bridge:

$V_{bridge} := 12V$

$I_{bridge} := 1A$

$t_{bridge} := .5hr$

$P_{bridge} := V_{bridge} \cdot I_{bridge} = 12\,W$

$E_{bridge} := P_{bridge} \cdot t_{bridge} = 2.16 \times 10^{4}\,J$

$E_{bridge} := 6W \cdot hr$

Microcontrollers:

$V_{micro} := 12V$

$I_{micro} := .5A$

$t_{micro} := .5hr$

$P_{micro} := V_{micro} \cdot I_{micro} = 6\,W$

$E_{micro} := P_{micro} \cdot t_{micro} = 1.08 \times 10^{4}\,J$

$E_{micro} := 3W \cdot hr$

Total energy for communications and control systems:

$E_{cc} := E_{micro} + E_{bridge} + E_{switch} + E_{2cam} = 1.123 \times 10^{5}\,J$

Energy consumed by communications and control systems

$E_{cc} := 31.19W \cdot hr$

Appendix M: Power Trade-Off Assessment

Table M: Power Trade-Off Assessment

Battery Network	Advantages	Disadvantages
Two Battery Network	Potentially less weight Potentially less cost One less battery to charge	Possible voltage fluctuations caused by high current pull on excavation system.
Three Battery Network	Allows for Independent power to the communications and control system. (Reliability) Ability to choose a more suitable battery for a specific situation.	Potentially more weight Potentially higher cost More batteries to charge.

Appendix N: Control System Details

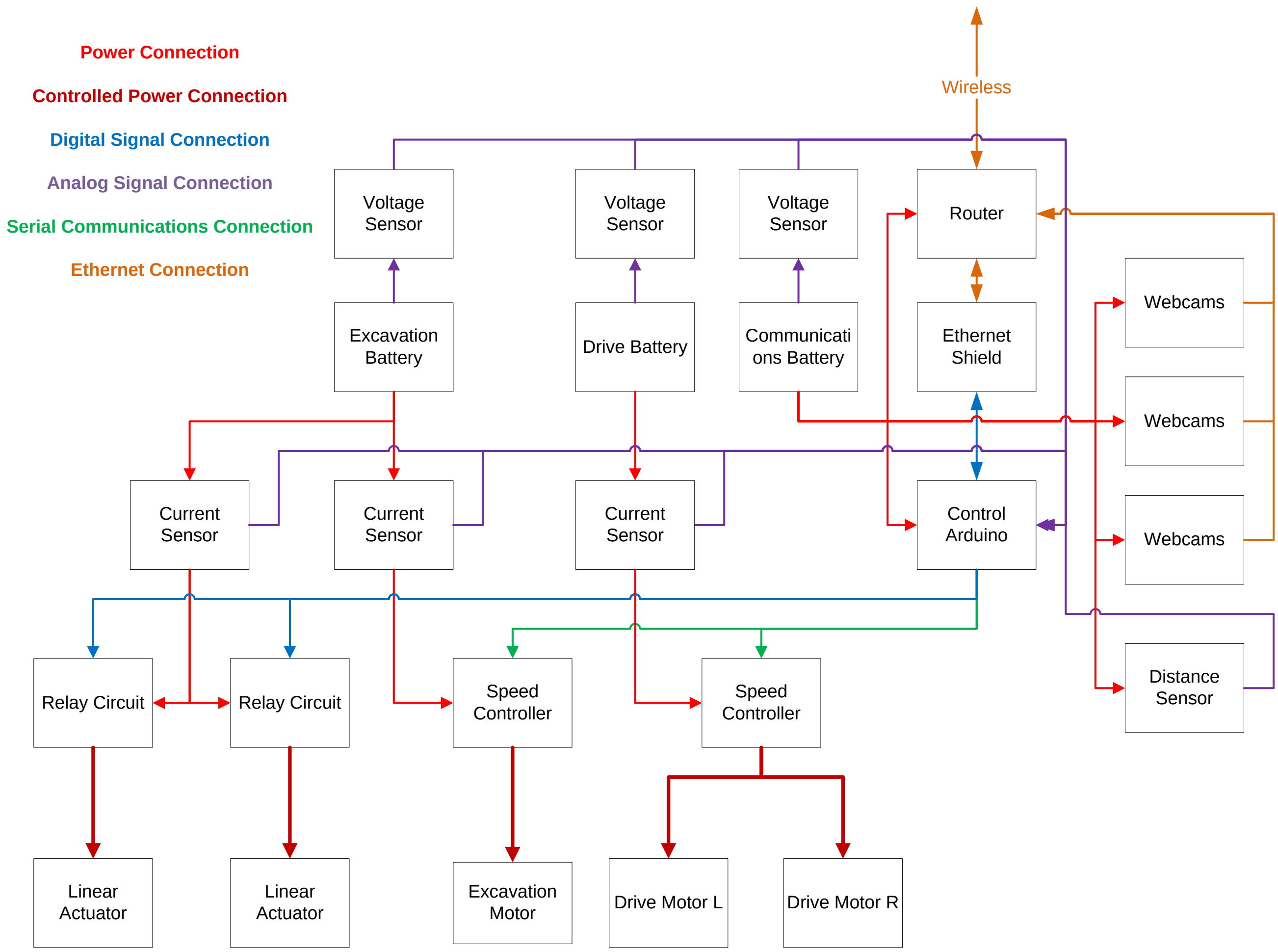


Figure P: Control System Details

Appendix O: Control System Trade-Off Assessment

Table Q: Control System Trade-Off Assessment

	Control	
	Advantage	Disadvantage
SPA	Simplified assembly process	Each sensor requires dedicated microcontroller to serve as SPA compliant interface
	Simplified interface with sensors	High cost
		High complexity with sensors
		Less available
Gumstix controller	Powerful	High expense
	USB hub interface included	
Arduino microcontroller	Less expensive	Requires purchase and interface with an Ethernet USB hub
	Adequate resources to control Lunabot	Fewer capabilities
	Many available resources for coding for ease of interfacing with sensors and components	

Appendix P: Communication System Details

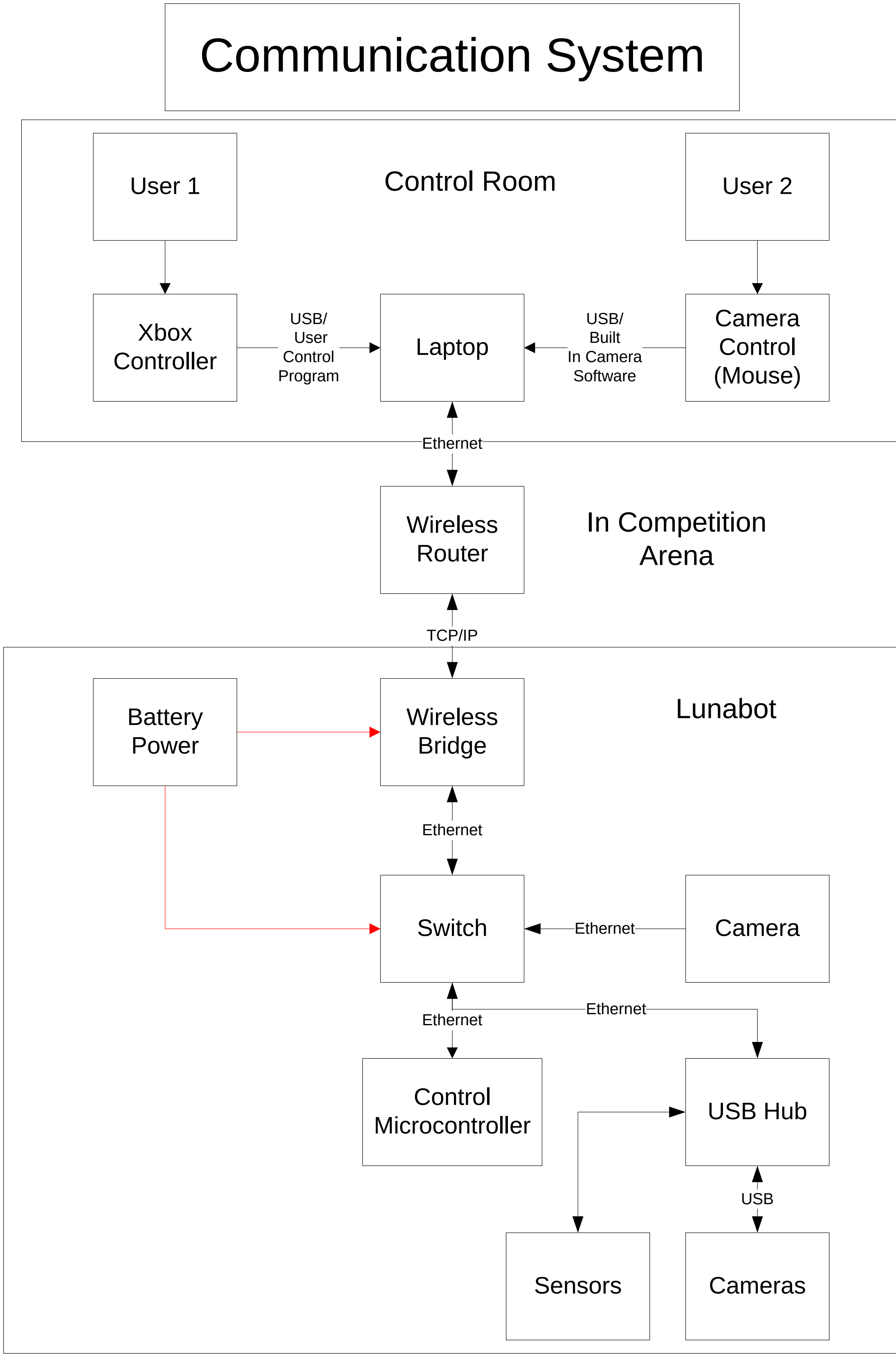


Figure N.1: Communications Concept of Operations Flow Chart

- User Control

Figure N.2: X-Box Controller Commands

Appendix Q: Communication Trade-Off Assessment

Table O: User Control Options

User Interface	Advantages	Disadvantages
X-Box controller	Easily handles 2 variable speed outputs	Does not have a third joystick for 3 variable controls
	Allows for up to 9 levels	
	Intuitive control interface already understood by users	
	Programming resources available	
Joystick	Many variations available with possibility for many buttons	Only has 1 joystick
Keyboard	Free	No variable inputs
	Already interfaced with laptop	
	Most available inputs	
Autonomous	No user control necessary	Very Complex
		Needs extra sensors onboard Lunabot

Appendix R: Schedule

Table R: Schedule

		Task Name	Duration	Start	Finish
10		Research Communications Options	19 days?	Sat 10/2/10	Tue 10/26/10
11		Compare Communications Options	10 days?	Fri 10/15/10	Wed 10/27/10
12		Select Communication Design	1 day?	Thu 10/28/10	Thu 10/28/10
13		Refine/Design Communication Design	32 days?	Fri 10/29/10	Thu 12/9/10
14		Mechanical Design	51 days	Sat 10/2/10	Tue 12/7/10
15		Research Mechanical Options	38 days?	Sat 10/2/10	Fri 11/19/10
16		Select Collection Design	3 days	Fri 10/15/10	Tue 10/19/10
17		Select Movement Design	4 days	Mon 10/11/10	Thu 10/14/10
18		Select Frame Design	5 days	Thu 11/18/10	Wed 11/24/10
19		Select Bin/Ejection Design	5 days	Thu 10/28/10	Wed 11/3/10
20		Refine/Design Systems	45 days?	Mon 10/18/10	Tue 12/14/10
21		Prepare for First Design Review	7 days	Mon 11/1/10	Tue 11/9/10
22		First Design Review	0 days	Wed 11/10/10	Wed 11/10/10
23		Testing Previous Lunabot	23 days	Sat 10/2/10	Mon 11/1/10
24		Parts Acquisition	26 days	Wed 11/3/10	Mon 12/6/10
25		Prepare First Draft of Written Report	6 days	Wed 11/10/10	Tue 11/16/10
26		First Draft of Written Report	0 days	Thu 11/18/10	Thu 11/18/10
27		Complete TAP and prepare 2nd draft of Final Report	11 days	Thu 11/18/10	Thu 12/2/10
28		TAP Complete, 2nd draft	0 days	Thu 12/2/10	Thu 12/2/10
29		Complete Final Report	9 days	Fri 12/3/10	Tue 12/14/10
30		Final Report Due	0 days	Wed 12/15/10	Wed 12/15/10
31		Prototype Fabrication	44 days	Thu 12/16/10	Tue 2/15/11
32		Testing	76 days	Thu 12/16/10	Thu 3/31/11
33		Modification	69 days	Wed 2/16/11	Sat 5/21/11
34		Prepare Testing Plan Review	7 days	Wed 3/23/11	Thu 3/31/11
35		Testing Plan Review Complete	0 days	Thu 3/31/11	Thu 3/31/11
36		Conduct Outreach Projects (NASA)	110 days	Tue 11/9/10	Thu 4/7/11
37		Outreach Report Due (NASA)	0 days	Mon 4/18/11	Mon 4/18/11
38		Prepare Systems paper (NASA)	116 days	Thu 11/11/10	Tue 4/19/11
39		Systems Paper Due (NASA)	0 days	Tue 4/19/11	Tue 4/19/11
40		Prepare Slide Show (NASA)	64 days	Wed 1/12/11	Mon 4/11/11
41		Prepare Team Pic and Bio (NASA)	64 days	Wed 1/12/11	Mon 4/11/11
42		Travel to Florida	2 days	Sat 5/21/11	Mon 5/23/11
43		Nasa Competition	6 days	Tue 5/24/11	Tue 5/31/11
44		Prepare for Senior Design Presentation	3 days	Sat 10/23/10	Tue 10/26/10
45		Senior Design Presentation	0 days	Tue 10/26/10	Tue 10/26/10
46		Bentonville Engineering Fair	0 days	Tue 11/9/10	Tue 11/9/10

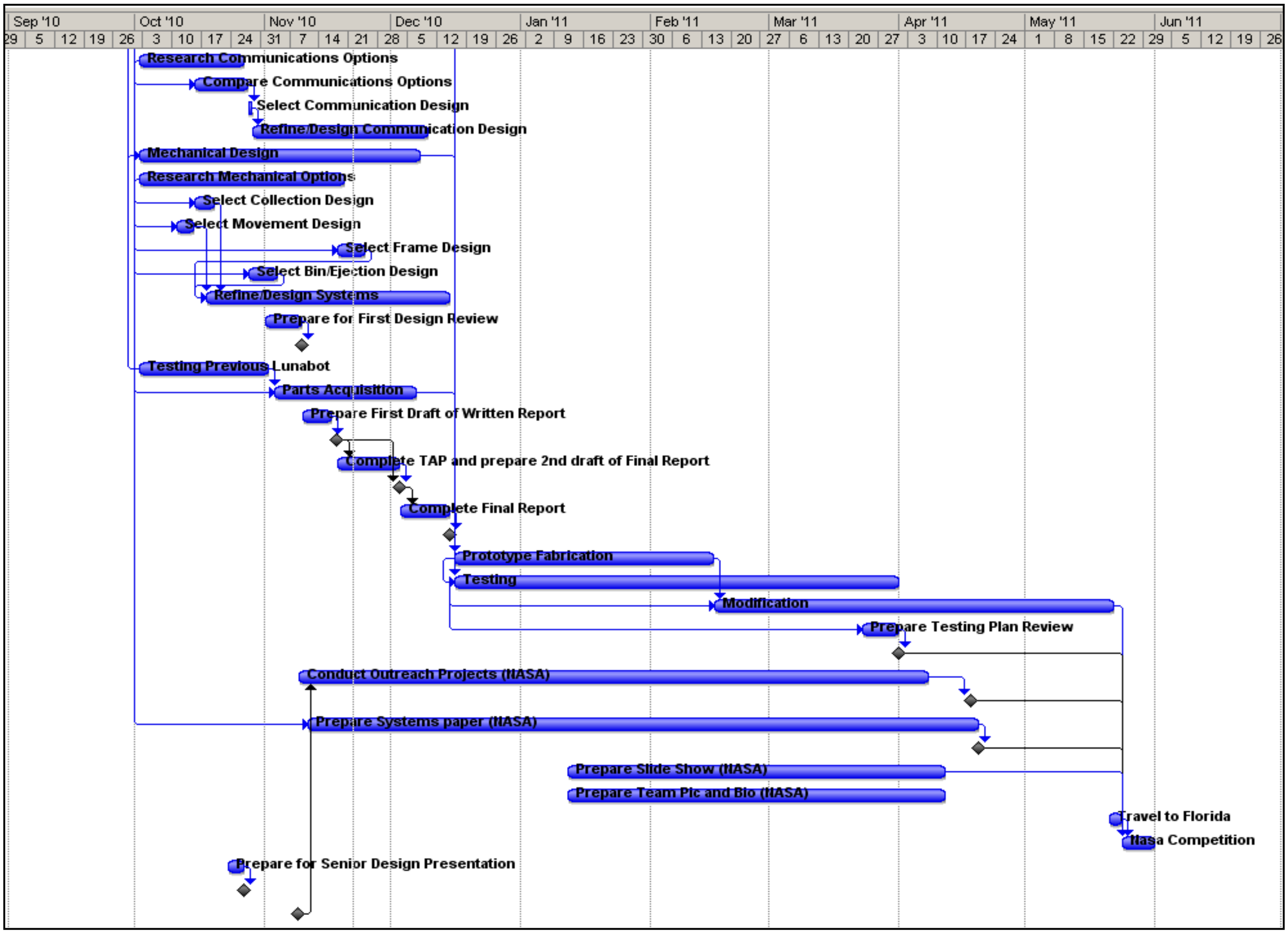


Figure R: Gannt Chart

Appendix S: Budget

Table S.1 shows the budget created at the beginning of the semester.

Table S.1: Preliminary System Budget

Preliminary Budget	
Outreach	$50.00
Team Spirit - Shirts, etc.	$50.00
Documentation	$100.00
Lunabot	$4,934.86
Competition	$3,365.14
Total	$8,500.00

Table S.2 shows the actual subsystem expenses, including spare parts.

Table S.2: Subsystem Expenses

System	Expenses
Power System	$1,384.26
Communications System	$143.54
Control System	$598.78
Mobility System	$588.68
Collection System	$937.37
Storage System	$478.60
Ejection System	$186.10
Frame System	$601.83
Total Cost	$4,919.16